

NUCLEAR PROSPECTORS OF EARTH AND SPACE OBJECTS

Ye. M. Filippov

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| 16. Abstract Nuclear geophysics is recounted in this book, beginning with a treatment of the distribution of radioactive elements in the land, sea, and meteorites. Nuclear unmanned prospecting landers intended for use on Mars, Venus, the Moon, and Jupiter are described. Nuclear densimeters, moisture meters, specialized element detectors, well-logging devices, neutron and x-ray tubes are described as developed in the USSR and abroad. Particle accelerators as applied in geophysics and geology are discussed. | | | | | |
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AUTHORS' ABSTRACT

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This book recounts the peaceful use of nuclear radiation-prospectors of material comprising various earth objects and celestial bodies. In it is presented in popularized form information about diverse nuclear methods and devices used in studying the earth's depth, the Moon, Venus, and other planets. In the concluding section, the main tasks yet to be solved by science in the near future are outlined.

The book is addressed to a wide range of readers.

"Let the atom be a worker, and not a soldier."

V. S. Yemel'yanov

Atom i mir

/Atom and Peace/

/5

FOREWORD

The idea of understanding the composition and structure of the earth, its depth, as well as the oceans and seas has long fascinated mankind. Man's glimpses have long been directed toward other celestial objects as well -- the Moon, Mars, Venus, and the universe as a whole. Until recently, meteorites were the only visitors from space to earth. At the present time spacecraft are studying the universe. Diverse devices for studying rocks and space have been landed via spacecraft on the surface of the Moon. Samples of lunar rock have been brought back to the earth for their direct study. Regular explorations of Venus and Mars are underway. Already the first reports have been obtained about the composition of their atmosphere, pressure, and temperature. Study of the solid shells of these planets is on the agenda.

However, in studying space, people have not forgotten about the earth, of which as a whole not so very much is known. Thus far we can reliably evaluate only the composition and structure of its uppermost shells -- the earth's crust not more than 30 km thick. But the earth radius has been estimated to average 6371 km. From this it is clear that the thickness of the earth's crust is less than 0.5% of an earth's radius. Comparing the globe with a hen's egg, the layer of the crust will roughly correspond to the thickness of the shell of the egg. Man can evaluate the deeper-lying layers of the earth only on the basis of diverse indirect data. A great deal yet remains to be done for a detailed study of the earth.

Data on the composition of the diverse earth objects are necessary not only in understanding the earth, but also for exploring, prospecting, and exploiting a great many minerals used in many sectors of the national economy.

Classical methods of determining the composition of rocks, ores, and water include the methods of analytical chemistry, spectral techniques, and several others. To conduct analyses with these techniques it is necessary to take samples of rocks and ores, bring them to the laboratory, convert them into a finely ground powder, and only then subject them to analysis. All these are extremely laborious and at times expensive processes.

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The technique of determining the composition of geological objects is greatly simplified by using various nuclear-physical methods. Some atoms of chemical elements disclose themselves by emitting various nuclear particles penetrating through considerable thicknesses of matter. Therefore the content of radioactive elements in rocks can be judged by measuring nuclear particles emitted by the nuclei of the atoms of these elements. The content of other chemical elements in rocks and ores can be judged by the action of external nuclear radiation from various sources striking them and by measuring induced radioactivity or by measuring various secondary nuclear particles generated in rock when acted on by primary radiation.

Thus, by sending into rock various nuclear particles -- these are unusual microprospectors, one can evaluate rocks, ores, and other geological materials. Many geological problems here can be solved without taking samples, by directly irradiating rocks at their bedding site -- in test wells, mine workings, and so on. Thus on the **borderline** of physics, mathematics, chemistry, geology, radio electronics, and other sciences there has risen a new geological science -- nuclear geophysics, or nuclear prospecting.

In this book, the first attempt is made to tell the reader about achievements in nuclear geophysics that are used in studying earth and space objects. In it the fundamentals of various nuclear-physical methods are presented in a very accessible manner and instruments used in solving diverse geological and other problems are described.

The book does not pretend to satisfy the demands of all readers. Some are satisfied with simple and elementary treatment, while others prefer formulas to lengthy explanations; still others are interested in detailed layouts of the instruments described, while there are those who are interested in specific results of investigations; there is yet another group who are interested in individual specialized problems considered in the various chapters, and so on. The author does by no means assume that all he has planned has achieved its appropriate level. Nonetheless he hopes that in this book many of the above-listed categories of readers will find something useful.

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NUCLEAR PROSPECTORS OF EARTH AND SPACE OBJECTS

Ye. M. Fillipov

CHAPTER ONE

7

HOW DID NUCLEAR PROSPECTING GET STARTED?

1. Discovery of Natural Radioactivity

Nuclear prospecting was born with the vigorous development of atomic and nuclear physics. The founder of these sciences was the great British physicist Ernest Rutherford (1871-1937), who advanced as early as 1891 the idea of the complex structure of the atom, and the possibilities of its fission and disintegration. The birth of atomic physics is associated with the discovery in 1895 by W. K. Roentgen (1845-1923) of X-rays, later to be named after him, and the discovery in 1897 by J. J. Thomson (1856-1940) of the electron. With the discovery in 1896 by A. Becquerel (1892-1908) of the natural radioactivity of uranium, nuclear physics emerged and began to develop. The rays discovered by A. Becquerel freely penetrate through bodies that are opaque to visible light. The properties of these rays began to be systematically explored by the couple Pierre Curie (1859-1906) and Marie Sklodowska-Curie (1867-1934), who discovered in 1898 the radioactivity of thorium, polonium, and radium. M. Curie called the emission of atoms of uranium and other elements radioactivity.

These discoveries made it possible for E. Rutherford and others to substantively engage in studying radioactivity and atomic structure. Thus, in 1899 E. Rutherford discovered alpha- and beta-rays and jointly with F. Soddy established the law of the radioactive decay of atoms. In 1900 Willard discovered an even more strongly penetrating radioactive emission -- gamma-rays.

In 1902 E. Rutherford and F. Soddy showed that radioactivity is the spontaneous decay of atoms, resulting in the formation of new chemical elements. Thus, the successive decay of uranium and thorium leads ultimately to the formation of isotopes of lead and helium atoms. In 1911 E. Rutherford and his students

* Numbers in the margin indicate pagination in the foreign text.

established the existence of the atomic nucleus. They proposed the planetary model of atomic structure, and later made other pioneering investigations in nuclear physics.

After the discovery of radioactivity, scientists in many countries began the detailed study of natural objects: elements, minerals, rocks, water, air, and so on. Along with the elements of the uranium, thorium, and other series, approximately another 180 naturally radioactive isotopes were found in nature and their total number reached 230. Of these, most exhibited weak radioactivity. There were only 67 highly active isotopes. Each isotope was characterized with its atomic number Z and mass A . For chemical elements the quantity A characterizes atomic weight. /8

Each radioactive isotope has its own specific decay period (T), that is, a period of time during which on the average half the atoms of a given radioactive substance decays. In nature, of the radioactive elements the isotopes of uranium with mass 238 (uranium-238) and thorium with mass 232 (thorium-232) are the most common. They have half-life periods of $4.51 \cdot 10^9$ and $1.39 \cdot 10^{10}$ years, respectively. Several other naturally radioactive isotopes have even longer half-lives. Thus, gadolinium-152 has a half-life of $1.1 \cdot 10^{14}$ years, and vanadium-50 -- $6 \cdot 10^{15}$ years, and so on.

One hundred ten stable isotopes have been established in nature. Many of these must also be viewed as unstable with very long half-life periods yet to be established.

With the measurement of the radiation of radioactive elements the possibility arose of searching and prospecting for radioactive and associated ores. Moreover, the different content in rocks of radioactive elements enabled geologists and geophysicists to evaluate the rocks as such that are indistinguishable to the naked eye or concealed beneath shallow overburden.

2. Discovery of Artificial Radioactivity and Nuclear Fission

In 1930 P. Dirac predicted the existence of the first anti-particle -- the positron (an electron with a positive charge). Two years later, this particle was discovered in cosmic rays by C. Anderson. In 1931 W. Pauli presented a hypothesis of the existence of the neutrino -- a neutral particle with a very low weight. A heavier neutral particle -- the neutron -- was discovered in 1932 by J. Chadwick. A prediction of this particle was made by E. Rutherford back in 1920. D. D. Ivanenko and independently of him, W. Heisenberg, advanced in 1932 the hypothesis of the neutron-proton structure of atomic nuclei.

Extremely important for nuclear physics and especially nuclear geophysics was the 1934 discovery by the couple E. Curie (1897-1956) and F. Joliot-Curie (1900-1958) of the artificial radioactivity of nuclei. By irradiating matter with alpha-particles, they directed attention at the appearance in the matter of artificially radioactive nuclei. This discovery subsequently enabled physicists and geophysicists to develop methods of analyzing matter activated by exposure to various kinds of nuclear radiation. 49

A key stage in the progress of nuclear physics was the year 1939, when L. Meitner and O. Frisch, in interpreting the experiments of O. Hahn and F. Strassmann, discovered the fission of uranium when exposed to neutrons. Independently of them, the same conclusion was reached by E. and F. Joliot-Curie. In this same year Ya. I. Frenkel' and independently of him, Niels Bohr and J. Wheeler, formulated the theory of the fission of the atomic nucleus. In 1940 G. N. Flerov and K. A. Petrzhak discovered the spontaneous fission of uranium nuclei into fragments. Discovery of nuclear fission, upon bombardment with neutrons, into fragments with the emission of two to three neutrons made possible chain nuclear reactions and mastery of the energy of the nucleus.

Scientists had known that enormous energy was locked in the uranium nucleus since the beginning of this century. The brilliant prediction that this energy would be of great service to mankind was made in 1910 by V. I. Vernadskiy (1863-1945). Subsequently, he repeatedly called on scientists to discover this energy and to place in service their high and humane ideals. However, V. I. Vernadskiy understood that mastery of atomic energy would require sufficient quantities of the required raw material. So on his initiative in 1913 there began the first prospecting for deposits of radioactive ores in Russia.

The first controlled nuclear reaction was achieved on 2 December 1942 under the supervision of E. Fermi (1901-1954).

During this time the first atomic reactor was commissioned in the United States in great secrecy. Under pressure by the military and against the aspirations of the peoples, American scientists to compel, no matter the cost, atomic energy to serve in war, resulting in the tragedy of Hiroshima and Nagasaki.

The atomic threat also hung over our country. Accordingly, Soviet scientists began extensive research into mastering atomic energy. The first atomic reactor in our country was commissioned on 26 December 1946 under the supervision of I. V. Kurchatov (1903-1960). Soon atomic weapons were developed in the USSR for the country's defense.

After testing its first atomic bomb, the Soviet Union appealed to all countries to use atomic energy for peaceful purposes and showed its example when on 27 June 1954 the world's first atomic power station was set up and commissioned.

Powerful beams of neutrons produced in atomic reactors can be used to make various artificially radioactive isotopes. In the USSR these isotopes began to be produced in large quantities since 1948. Since then, applied nuclear physics began vigorous progress. Nuclear radiation of isotopic sources has found wide use in science, technology, medicine, biology, and the national economy. At the same time, radioisotope sources began to be used as nuclear prospectors in the irradiation of geological objects for their investigation. These objects were found amenable to study not only based on the artificial radioactivity induced therein, but also by means of various secondary radiation formed when primary radiation bombards their atoms and nuclei. /10

3. Structure of Matter

Each substance is made up of molecules and atoms. Combinations of like molecules, or nearly alike, form materials. Rocks constituting the earth's crust and the surface layer of the Moon and other planets are diverse combinations of minerals.

Atoms consist of nuclei surrounded by electrons. Atoms, nuclei, and electrons are extremely small. Thus, the radius of an atom is about 10^{-8} cm, the radius of nuclei is about 10^{-13} to 10^{-12} cm, and that of electron is $3 \cdot 10^{-13}$ cm. All nuclei of atoms consist of nucleons (protons and neutrons). An exception is represented by ordinary hydrogen, whose nucleus consists of a single proton. The number of protons in a nucleus and the number of orbital electrons in an atom determines its charge and is called the atomic number of the element and its isotopes Z in accordance with the table of D. I. Mendeleev. The total of the masses of protons and neutrons in the nucleus determines its mass and thus the atomic weight of the element A , 10^{-27} to 10^{-23} g. The weight of an electron as we know is roughly 1800 times smaller than a nucleon. Currently, 105 chemical elements (Table 1) are known. Of these, 92 are encountered in nature; the rest are synthesized artificially in laboratories.

Most chemical elements encountered in nature consist of several isotopes, that is, nuclei with the same number of protons and with a different number of neutrons. At the present time, in nature 340 isotopes have been recorded; of these, as already noted, 230 are radioactive, and the remained are stable. Also, more than 1000 artificially radioactive isotopes have been obtained in laboratories.

TABLE 1. PERIODIC SYSTEM OF ELEMENTS OF D. I. MENDELEYEV

| | | | | | | | | | | | | | | | | | |
|---------------------|----------------------|---|------------------------|------------------------|----------------------|----------------------|---------------------|---------------------|----------------------|---------------------|--------------------|----------------------|----------------------|---------------------|---------------------|---------------------|---------------------|
| 1 H Водород | | | | | | | | | | | | | | | | | 2 He Гелий |
| 3 Li Литий | 4 Be Бериллий | | | | | | | | | | | 5 B Бор | 6 C Углерод | 7 N Азот | 8 O Кислород | 9 F Фтор | 10 Ne Неон |
| 11 Na Натрий | 12 Mg Магний | | | | | | | | | | | 13 Al Алюминий | 14 Si Кремний | 15 P Фосфор | 16 S Сера | 17 Cl Хлор | 18 Ar Аргон |
| 19 K Калий | 20 Ca Кальций | 21 Sc Скандий | 22 Ti Титан | 23 V Ванадий | 24 Cr Хром | 25 Mn Марганец | 26 Fe Железо | 27 Co Кобальт | 28 Ni Никель | 29 Cu Медь | 30 Zn Цинк | 31 Ga Галлий | 32 Ge Германий | 33 As Мышь-ак | 34 Se Селен | 35 Br Бром | 36 Kr Криптон |
| 37 Rb Рубидий | 38 Sr Стронций | 39 Y Иттрий | 40 Zr Цирконий | 41 Nb Ниобий | 42 Mo Молибден | 43 Tc Технеций | 44 Ru Рутений | 45 Rh Родий | 46 Pd Палладий | 47 Ag Серебро | 48 Cd Кадмий | 49 In Индий | 50 Sn Олово | 51 Sb Сурьма | 52 Te Теллур | 53 I Йод | 54 Xe Ксенон |
| 55 Cs Цезий | 56 Ba Барий | 57 по 71 редкие земли, Лантаноиды | 72 Hf Гафний | 73 Ta Тантал | 74 W Вольфрам | 75 Re Рений | 76 Os Осений | 77 Ir Иридий | 78 Pt Платина | 79 Au Золото | 80 Hg Ртуть | 81 Tl Таллий | 82 Pb Свинец | 83 Bi Висмут | 84 Po Полоний | 85 At Астатин | 86 Rn Радон |
| 87 Fr Франций | 88 Ra Радий | 89 по 103 редкие элементы, Актиниды | 104 K Курчатовий | 105 N Нильсборий | | | | | | | | | | | | | |

Lanthanides

| | | | | | | | | | | | | | | |
|---------------------|-------------------|-------------------------|--------------------|----------------------|----------------------|----------------------|-----------------------|---------------------|------------------------|------------------------|---------------------|-------------------------|------------------------|------------------------|
| 57 La Лантан | 58 Ce Церий | 59 Pr Прозермид | 60 Nd Неодим | 61 Pm Прометий | 62 Sm Самарий | 63 Eu Европий | 64 Gd Гадолиний | 65 Tb Тербий | 66 Dy Диспрозий | 67 Ho Гольмий | 68 Er Эрбий | 69 Tm Тулий | 70 Yb Иттербий | 71 Lu Лютеций |
| 89 Ac Актиний | 90 Th Торий | 91 Pa Протактиний | 92 U Уран | 93 Np Нептуний | 94 Pu Плутоний | 95 Am Америций | 96 Cm Кюрий | 97 Bk Берклий | 98 Cf Калифорний | 99 Es Эйнштейний | 100 Fm Фермий | 101 Md Менделевий | 102 (No) Нобелий | 103 Lr Лоуренсий |

Actinides

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

TABLE 2. MEAN COMPOSITION OF EARTH'S CRUST, WEIGHT %
(AFTER A. Ye. FERSMAN)

/12

| Element | Content | Element | Content | Element | Content |
|----------|---------|-----------|---------|----------|---------|
| Oxygen | 49.13 | Calcium | 3.25 | Hydrogen | 1.00 |
| Silicon | 26.00 | Sodium | 2.40 | Titanium | 0.61 |
| Aluminum | 7.45 | Potassium | 2.35 | Carbon | 0.35 |
| Iron | 4.20 | Magnesium | 2.35 | Chlorine | 0.20 |

4. Objects Studied

In his practical activity, man is making ever-growing use of the riches of the earth's depths: petroleum, coal, iron, copper, lead, uranium, as well as construction stone, groundwater, and the like. Diverse geophysical methods are enlisted in searching for, prospecting for, and exploiting minerals. No small role here is played by methods of nuclear geophysics, with which -- as already remarked -- one can determine the content in rocks of chemical elements and evaluate their content of useful constituents, as well as the density of rocks and ores, and so on. Accordingly, we must briefly discuss the composition of the earth's crust accessible to man in his activity.

As has been shown, the earth has a mean radius of about 6371 km. Only its upper layer, about 30 km in thickness, called the earth's crust, has been studied most closely. The earth's crust contains all chemical elements from hydrogen to uranium. However, the content of chemical elements in the earth's crust varies within very broad limits -- tens of a percent to thousandths and millionths of a percent. One can judge the presence of the principal rock-forming chemical elements from the data in Table 2. The most common elements in the earth's crust are oxygen, silicon, and aluminum (82.58% of the weight of the entire crust). The first nine elements account for 98.13%, the first 12 -- 99.29%, and all the remaining elements in the earth's crust account for only 0.71%. Thus, beryllium is present to the extent of only $3 \cdot 10^{-4}\%$, uranium -- $4 \cdot 10^{-4}\%$, gold -- $4 \cdot 10^{-7}\%$, and protactinium -- to as low as $7 \cdot 10^{-11}\%$.

The elemental content values in Table 2 are averaged over the entire crust of the earth. However, in rocks the content of elements can fluctuate in broad limits. Increased (ore) accumulations of a particular mineral are observed in some types of rocks. These accumulations of ore minerals are specially searched

for by geologists and geophysicists in order to recover and extract from them elements and their compounds vital to the national economy.

In searching for, prospecting, and exploiting minerals by the classical techniques, samples are collected, crushed, and ground. The sample thus prepared is analyzed by chemical and physicochemical, or physical methods. From the findings of these analyses geologists then evaluate the presence in rocks and ores of a particular element and the suitability of these ores at the present stage of technology for extraction.

Determining the content in rocks of elements by the above-mentioned techniques is fraught with numerous difficulties. /13
Moreover, at the present time when geological studies are taking on a broad scale, year by year the number of samples collected for analysis is mounting. Naturally, in these conditions it is necessary to convert from laborious and time-consuming techniques to more progressive ones. In particular, these include methods of nuclear physics, with which -- as will be shown below -- it is possible to determine rapidly and with a high sensitivity threshold the content in samples of chemical elements and their isotopes.

The advantage of nuclear methods compared with others also lies in the fact that by using nuclear methods the content of numerous elements in rock can be determined not only in laboratory conditions, but even right at the location at which the rocks and ores investigated come to light -- in outcroppings, mine workings (trenches, prospecting pits, drifts, and shafts) and from the profile of drill cores.

The composition of the Moon and other celestial bodies is evaluated mainly from various hypothetical data. Here, for example, it is assumed that the Moon and the Earth have a common origin and therefore must not differ widely in chemical composition. However, this awaited proof, which became possible only when spacecraft were built. A whole series of stations equipped with instruments, including nuclear-geophysical devices, were landed on the lunar surface for this purpose. Using these instruments, more reliable information on our satellite was secured. Subsequently, this information was verified with samples of rock brought to Earth via the manned spacecraft Apollo 11, Apollo 12, the Luna 16 automatic station, and others. These data on lunar rocks will be examined below.

CHAPTER TWO

RADIOACTIVE ELEMENTS MAKE THEMSELVES KNOWN

1. Natural Radioactivity

Rocks and other geological objects contain also naturally radioactive chemical elements, along with nonradioactive chemical elements. These naturally radioactive elements emit nuclear particles differing in kind and energy. By recording them, one evaluates the nature of emitting radioactive elements. Thus, alpha radiators make themselves known. Investigators studying natural objects continually make use of this property of radioactive nuclei. /14

Of the naturally radioactive elements, the most common are the families of uranium (uranium-radium), thorium, and actinium (actino-uranium, or uranium-235), and a lone isotope -- potassium-40. All these isotopes are long-lived and have existed since the formation of the Earth. Thus, the parent of the first family, uranium-238, has a half-life $T = 4.51 \cdot 10^9$ years. Undergoing 14 successive decay acts (eight alpha and six beta transformations), uranium-238 ultimately is converted into the stable isotope lead-206. Radium-226 ($T = 1622$ years) is its longest-lived radioactive decay product. Radium, even though a decay product of uranium, still can form independent deposits in terrestrial conditions. This is due to the fact that radium has a sufficiently long half-life and can via geochemical processes be transported from one place to another. Accordingly, in the study of the radioactivity of natural formations, the content of uranium and radium therein is determined separately.

Actinouranium ($T = 7.1 \cdot 10^8$ years) is an isotope of uranium, therefore in natural formations it is encountered together with uranium-238.

Undergoing successively seven alpha and four beta decays, actinouranium is transformed into the stable isotope lead-207. In natural uranium, actinouranium accounts for $1/140$, that is, 0.715%. Therefore in these formations it is usually not determined separately from uranium-238.

Of the above-noted radioactive elements, the longest half-life is exhibited by the isotope thorium-232 ($T = 1.39 \cdot 10^{10}$ years). Its successive decay (six alpha and four beta transformations) leads to the formation of the stable isotope lead-208. All radioactive decay products of thorium have relatively short half-lives,

therefore in geological formations thorium is found in equilibrium with its decay products.

In natural potassium, potassium-40 ($T = 1.25 \cdot 10^9$ years) accounts for 0.0119% or $1/8400$. However, since potassium in nature is seventh in occurrence (cf. Table 2), its isotope potassium-40 makes a marked contribution to the natural radioactivity of natural formations.

Summing up, we can note that natural radioactivity is caused mainly by uranium, radium, and thorium with their decay products, and by potassium-40. In natural formations other radioactive isotopes are also encountered. However, their content is not high, therefore in the study of the total natural radioactivity of rock and other objects they are usually not taken into account.

2. Natural Nuclear Reactor

/15

Above it was stated that in natural conditions the content of actinouranium is 0.715%. However, scientists have long been speculating as to whether this is always and everywhere the case. And now in recent years French scientists made a sensational discovery. In studying the ratio of uranium isotopes from a deposit in Gabon they established that the concentration of actinouranium varies in the range 0.612-0.730%.

Moreover, noticeable amounts of the following rare-earth elements were detected in the uranium ores of Gabon: neodymium, samarium, europium, and cerium. The isotopic composition of these elements wholly corresponds to composition of fission products accumulating in present-day nuclear reactors (see Section 4, Chapter Three).

In the view of many scientists, these data can serve as proof that hundreds of millions of years ago a nuclear chain reaction occurred in nature. At the same time, the content of actinouranium in the ores corresponded to 3%. It is precisely this concentration level of actinouranium in uranium fuel that is needed for the fission reaction in heavy water reactors.

3. Measurement of Radiation

Radiation passing through matter interacts with it, causing various effects. From these effects one judges the nature of the nuclear and atomic radiation.

In 1896, Henri Becquerel, using a photographic plate, discovered the natural radioactivity of uranium. Later, natural

radioactivity began to be measured with ionization chambers. The phenomenon of scintillation, discovered by W. Crookes in 1903, began to be used in measuring the radioactivity of samples only after the invention by Soviet engineer L. A. Kubetskiy, in 1930, of a light-sensitive instrument -- the photomultiplier (see below).

Various radiation receivers, usually called counters or detectors, were developed on the basis of the above-mentioned effects.

Alpha- and beta-particles are recorded directly based on the effects bearing the same name. Gamma-rays are usually recorded based on the electrons expelled in the substance. Neutrons, not directly ionizing matter, are recorded from the secondary effects leading to the formation of charged particles: recoil protons (nuclei of hydrogen H^1), alpha-particles (nuclei of helium He^4), tritons (nuclei of tritium H^3), and other particles generated in reactions with the nuclei of atoms of certain elements.

The ionization effect produced by a single particle in the radiation receiver is ordinarily weak, therefore it is amplified with special radiometric devices and thereupon recorded.

Currently, various kinds of ionization, scintillation, and semiconductor detectors are used in recording radiation. /16

Ionization detectors operate on the principle of an air capacitor, in which the central electrode serves as one of its plates, and the chamber wall -- as the other. The gas filling the space in the detector in ordinary conditions is an insulator, but when acted on by charged particles it becomes a conductor. Free electrons appear in it, plus positive and negative ions. If a potential difference is applied to the plates of this device in which ions are formed, the electrons and ions tend to move toward the electrodes and as a result, an electric current is produced, which can be recorded with a sensitive instrument connected into the circuit between the electrodes. The size of the ionization current of the detector depends both on the intensity of the ionizing radiation, and on the potential difference applied to its electrodes. Depending on the difference of the applied potentials and several other specific features, ionization detectors are subdivided into ionization chambers, proportional counters, and gas discharge counters.

Ionization chambers can operate in steady-state (integrating) and in pulsed regimes. This kind of detector is basically used for recording charged alpha- and beta-particles. And chambers operating in the integrating regime are used for measuring total beams of radiation, and pulsed chambers -- for measuring individual particles and their energies.

In proportional counters, the amplitude of the pulse arriving at the anode is proportional to the number of ions formed during initial ionization, and thus is proportional to the radiation energy. Thus, this kind of detector is used for determining radiation energy. Two types of proportional counters are used in nuclear geophysics: for recording soft X- and gamma-radiation with energies roughly in the 1-50 keV range ($1 \text{ keV} = 10^3 \text{ eV} = 1.6 \cdot 10^{-9} \text{ ergs}$) and neutrons. We note that X- and gamma-radiation are of the same electromagnetic nature and differ in wavelength. Accordingly, in the following treatment, in several cases we will understand either by the term gamma-radiation. Here we must naturally not forget that the spectrum of X-ray radiation is continuous with several characteristic lines, but the gamma-radiation spectrum is discontinuous.

Proportional counters for soft gamma-radiation are filled with inert gases: helium, neon, argon, krypton, and xenon (see Table 1). Usually, the lower the atomic number of the counter filling gas, the higher the resolution with which the particular radiation can be recorded. Thus, counters with neon are used in the spectrometry of gamma-radiation with energy in the range of approximately 1.5-3.5 keV; counters filled with argon are used in the spectrometry of gamma-quanta with energy in the range of approximately 3.5-6.5 keV, while those containing xenon are used for the spectrometry of gamma-radiation are used in the range of approximately 5-18 keV.

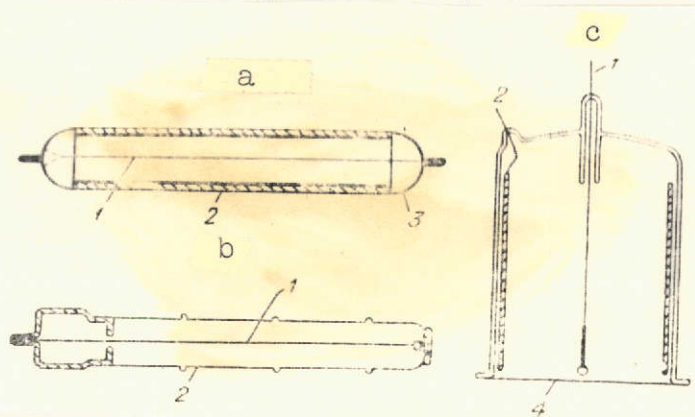


Fig. 2.1. Schematic view of cylindrical gamma- and beta-counters (a and b) and end-face beta-counter (c):

- | | |
|-------------|-------------------|
| 1. filament | 2. cathode |
| 3. cylinder | 4. counter window |

Proportional detectors for recording neutrons are filled with gases with the properties of the nuclei of atoms intensively capturing neutrons. These gases include the atomic isotope helium-3 and a compound of boron and fluorine (boron trifluoride).

Geiger-Mueller gas discharge counters are used for recording alpha- and beta-particles, as well as gamma-quanta. Using these counters, it is possible to measure only total beams of the radiations indicated.

Compared to the other ionization detectors, gas discharge counters find the greatest use. Therefore, it is convenient to use their diagram to become acquainted with the arrangement of ionization detectors in general. Schematic cross-sections of cylindrical gamma- and beta-counters and of the end-type beta-counter are shown in Fig. 2.1. A tungsten filament located along the counter axis serves as the counter anode, and a thin layer of metal deposited on the internal surface of the counter serves as the cathode. The cylinders of gamma-counters and end-type beta-counters are usually made of glass; the cylinder of cylindrical beta-counters is usually made of a thin layer of aluminum, simultaneously serving as the counter's cathode. The internal space of the counter is filled with gas. When charged particles strike the internal space of the counter, the gas is ionized. Acted on by an applied potential difference between the plates of the counter containing the ionized gas, leakage of current begins. From the magnitude of this current amplified by the device, one judges the intensity of the radiation being received.

Beta-particles penetrate the counter either through the counter body, or through a window in the end. End-type counters with a very thin window can be used not only for recording beta-particles, but also alpha-particles. /18

Gamma-radiation is recorded by way of the electrons dislodged from the counter cathode through the photo-effect and the Compton effect. The reader can become familiar with these effects in the following chapters.

Ionization chambers are similar in design to end-type counters. Proportional counters are usually cylindrical with a thin side window -- for the entrance of soft gamma-rays.

Proportional counters are similar to ionization chambers, however their space is filled not with gas, but with a solid semiconductor. Acted on by radiation, free charge carriers are produced in these detectors. Using this kind of detector, one can record charged particles and gamma-quanta with very high resolution.

Scintillation counters are a combination of scintillator (phosphor) and light-sensitive instrument -- photomultiplier (PM). The basic design of a photomultiplier is shown in Fig. 2.2. It has several dynodes -- emitters. Between the photocathode and the first emitter is applied a specific potential difference. From emitter to emitter, the potential difference steadily rises.

By acting on the phosphor, the nuclear particles cause flashes of light to appear in it. The light acts on the photocathode and dislodges electrons from it -- the so-called photo-effect takes place. Acted on by the potential difference applied between the photocathode and the first emitter of the PM, the electrons gain energy and eject, in turn, new electrons from the emitter. Since a higher potential difference, compared with the potential difference between the photocathode and the first emitter, is applied between the first and second emitters, the electrons in this space are again accelerated and reach the second emitter, and so on. The number of electrons ejected from emitter to emitter rises and charge is accumulated at the PM collector in the form of a current pulse. These currents are amplified with special electronic circuits. In order that during the acceleration the electrons are not scattered by the atoms of nitrogen and oxygen contained in the PM cylinder, a vacuum is produced in it.

Each device intended for recording nuclear radiation, depending on its purpose, contains -- besides radiation detectors -- amplification and other radioelectronic circuits: power block, block for the discrimination of current pulses, pulse scaling block, and so on. The simplest are devices intended for measuring overall radiation beams -- counting-rate meters. Devices used for determining the energy of charged particles and gamma-quanta are called spectrometers. An invariable component of these devices is the analyzer, which can be single-channel and multi-channel with channels numbering up to 4000 or more.

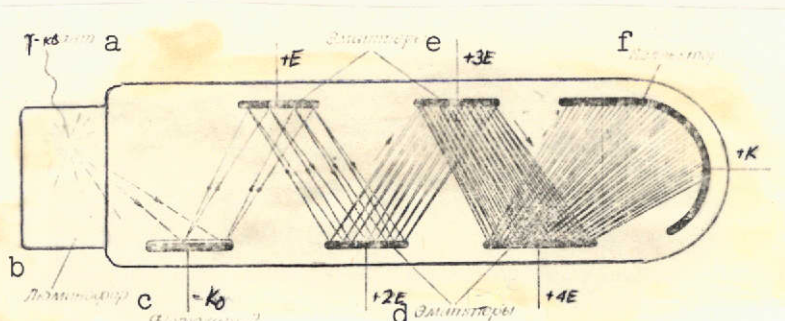


Fig. 2.2. Schematic diagram and operating principle of photomultiplier

KEY: a. gamma-quantum b. Phosphor
c. Photocathode d. Emitters
e. Emitters f. Collector

Depending on the field of use, radiometric devices are subdivided into laboratory type, field (portable and vehicle-carried), and drillhole type intended for studying drillholes. /19

4. Study of Natural Radioactivity of Geological Samples

In our country, the study of the natural radioactivity of rock, water, and air was begun in 1904 by the physicists I. I. Borgman in Petrograd and A. P. Sokolov in Moscow. In 1915 V. I. Baranov in Moscow began to become involved with this problem, making a substantial contribution to the development of radiometric and nuclear-geophysical methods in our country.

Natural radioactive elements emit alpha- and beta-particles as well as gamma-quanta. At the first stage of the study of the radioactivity of natural objects, alpha- and beta-methods were principally the techniques employed. Total sample radioactivity was determined with these methods. Currently, sample radioactivity is determined mainly by gamma- and beta-methods. The separate determination of uranium, radium, thorium, and potassium in samples is conducted in this case from the measurement of total beta-activity and using gamma-spectrometry with respect to individual reference lines. Whereas at first gamma-spectrometry was carried out with scintillation counters, since 1970 semiconductor germanium-lithium detectors with high resolution began to be used for this purpose. The graphs shown in Figs. 2.3 and 2.4 can serve as an example of the measurement of the spectral distribution of gamma-radiation from samples containing uranium. The germanium-lithium detector is 20.5 cm³ in volume, and the scintillation detector consists of a sodium iodide crystal activated with thallium, 100 m in height and 150 mm in diameter. An increase in the general background of spectral curves with decrease in energy is associated with the accumulation of scattered and bremsstrahlung radiation in sample and detector. From Fig. 2.3 we can see that considerably more lines appear in the spectrum measured with the germanium-lithium detector than in the spectrum measured with the scintillation counter. Thus, the uranium lines (uranium X₁ or thorium-234) with energies of 63 and 93 kev, and radium-B (lead-214) with 76 kev energy are merged into a single peak in the scintillation spectrum. /20

Ordinarily the reference lines with energy of 93 kev (thorium-234) and 185 kev (ionium or thorium-230) are used in the determination of uranium; usually lines with energy of 352 kev (thorium-234), 609 kev and 1.76 Mev (radium-C or bismuth-214) are used in the determination of radium. When determining thorium, one can use the reference lines with energy of 238 kev (thorium-B or lead-212) and 2.62 Mev (thorium-C²³⁴ or thallium-208). Potassium is determined based on the 1.46 Mev line (potassium-40).

In field conditions, principally the five-channel, model LSU-5k ("Laura") laboratory scintillation unit is used in analyzing rock samples for radioactive elements; a photograph of the model is shown in Fig. 2.5. Its design include two detectors (beta- and gamma-transducers). In the gamma-transducer the phosphor is a sodium iodide crystal 40x50 mm in size, from the FEU-13 photomultiplier; in the beta-transducer there is a layer of stilbene powder (50-60 mg/cm²) deposited on a plexiglas disk. The sensitivity threshold when measuring samples weighing 150-200 g with the LSU-5k corresponds to the following content values: (2-2.5)·10⁻⁴% uranium, (1-5)·10⁻⁴% radium in equilibrium uranium equivalent, (1-1.5)·10⁻⁴% thorium, and 0.2-0.3% potassium. The

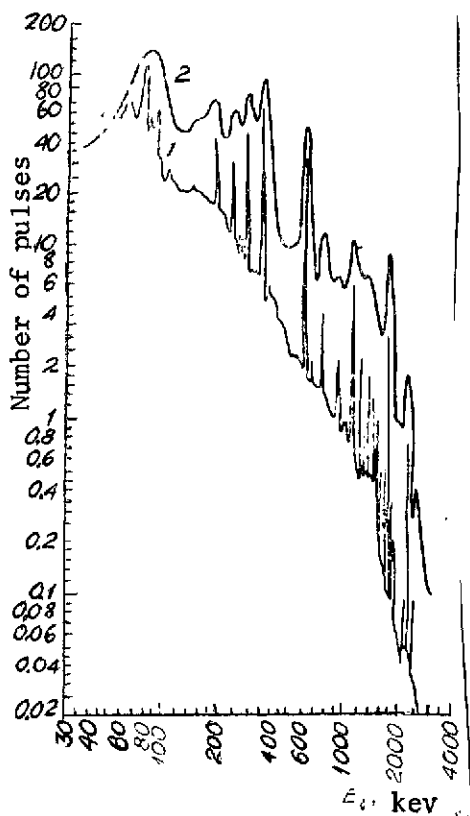


Fig. 2.3. Gamma spectra of uranium series elements, measured with a germanium-lithium detector (1) and a scintillation detector (2) in the 30 keV to 3 MeV range

measurement precision is 30% ^{/21} (higher concentrations are measured to higher precision). The time required to measure one sample is 30 min.

When measurements are made in the lead housing with 12 cm thick walls containing a 70x70 mm sodium iodide crystal and a 150 mm diameter beta-phosphor (from the FEU-49 photomultiplier), using samples weighing about 1 kg for 1 hr, the sensitivity threshold for the LSU-5k is raised by about four to five times.

In addition to the LSU-5k, multicomponent samples can also be measured with the 50-channel AI-50 amplitude analyzer ("Lin-ya"), the 100-channel AI-100-1 amplitude analyzer ("Raduga"), and so on. Thus, when he carried out measurements for 1 hr on samples weighing 1.5 kg and placed in a shaped cassette using the AI-100-1 analyzer with a low-background detector (a FEU-49 photomultiplier and a sodium iodide crystal 150 mm in diameter and 100 mm in height), placed in a low-background chamber, V. A. Bobrov obtained the following sensitivity thresholds: $7 \cdot 10^{-5}\%$ uranium with respect to radium; $1.6 \cdot 10^{-5}\%$ thorium; $7 \cdot 10^{-5}\%$ mesothorium-2 (in units of equilibrium thorium); and 0.02% potassium.

5. Content of Radioactive Elements in Natural Formations of the Earth

The content of radioactive elements in the upper layer of the earth's crust can be evaluated from studying rocks outcropping at the earth's surface or bored with drillholes. We note

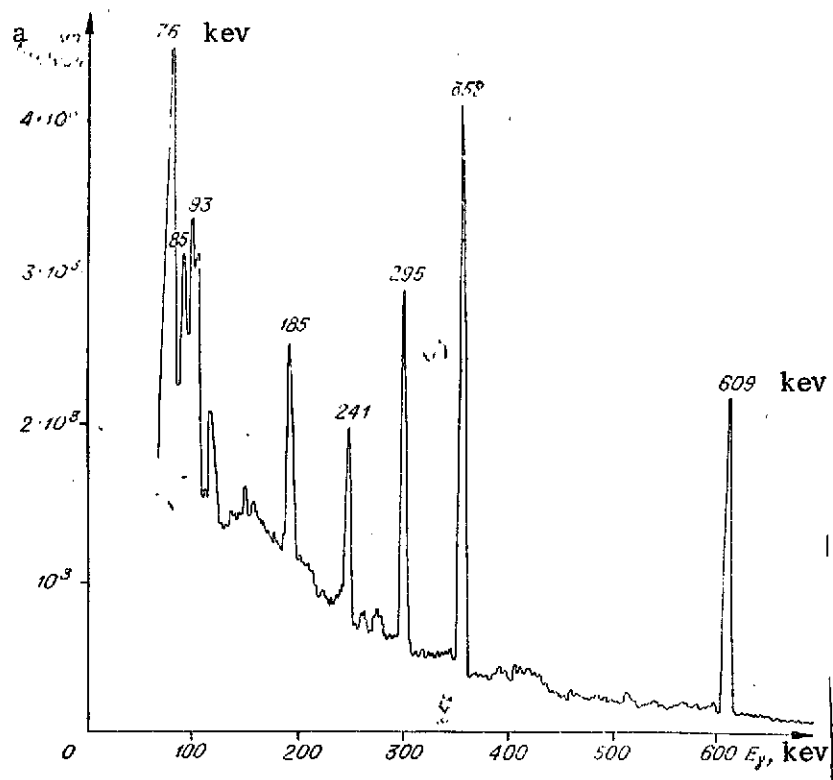


Fig. 2.4. Gamma-spectrum of uranium pitch measured with a semiconductor germanium-lithium detector in the low-energy range (50-700 keV)
KEY: a. N, pulses/10·min

that the deepest drillhole at the present time has a depth of 7724 m. Concentrations of radioactive elements at greater depths are estimated from a study of rocks that have surface outcroppings. Based on these data, A. P. Vinogradov showed that in the earth's crust the mean content of radioactive elements can be expressed in the following values: $1.2 \cdot 10^{-10}\%$ radium; $(2-4) \cdot 10^{-4}\%$ uranium; $1.2 \cdot 10^{-3}\%$ thorium; and 2.5% potassium. The radioactivity of deeper-lying layers can be evaluated only from indirect data based on hypothetical calculations of the temperature conditions within the earth and from a study of the composition of meteorites. Meteorites, according to one hypothesis,

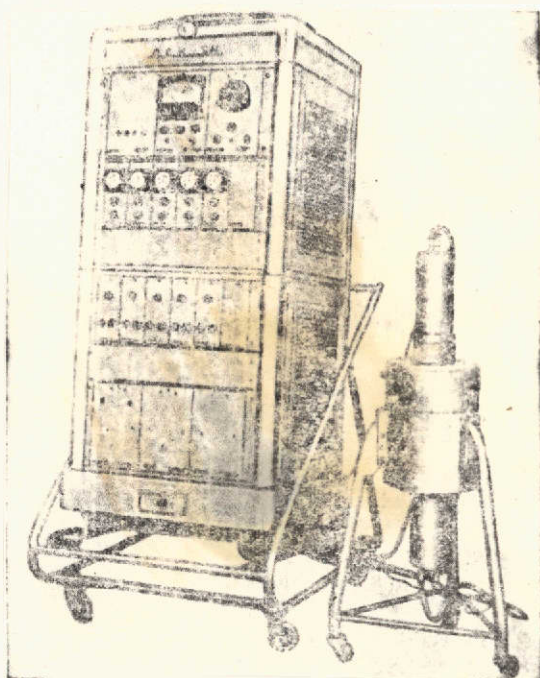


Fig. 2.5. General view of five-channel LSU-5k laboratory type scintillation unit ("Laura")

are viewed as fragments of the interior of planets similar to the earth. Stony silicate meteorites are regarded as fragments of the mantle located at depths from 30 to 2000 km from the earth's surface.

The mean content of radioactive elements therein is estimated by the following values: $1.3 \cdot 10^{-6}\%$ uranium, $4.3 \cdot 10^{-6}\%$ thorium, and 0.09% potassium. The concentrations of radioactive elements in the ferruginous core of the earth with a radius of 3470 km is established from their concentrations in iron meteorites. Note that their content of radioactive elements is 10 to 100 times lower than the corresponding value in stony meteorites.

The content of radioactive elements in the waters of the seas and the oceans is much less than in the surface layers of the earth. Thus, the concentration of radium in these regions is about $1 \cdot 10^{-16}$ g/cm³, uranium -- $(0.3-0.7) \cdot 10^{-9}$ g/cm³, thorium -- $1 \cdot 10^{-9}$ g/cm³, and potassium

$3 \cdot 10^{-4}$ g/cm³. The radium content

in rivers as a rule is lower or the same as in sea water, while the uranium content can vary within wide limits, from $3 \cdot 10^{-12}$ to $n \cdot 10^{-8}$ g/cm³. The radioactivity of the water in outlet lakes is not different from that of river water. The radioactivity of nondischarge lakes has a somewhat increased radioactivity compared with river water. Higher concentrations of radioactive elements are observed in stratal water compared to surface water. However, overall the uranium content therein varies from $1 \cdot 10^{-12}$ to $2 \cdot 10^{-3}$ g/cm³. Elevated radium concentrations are also found in the stratal waters of petroleum deposits.

The content of radioactive elements in atmospheric air is negligible. Thus, the content of radon (a gaseous decay product of radium) in curies/cm³ can be represented by the following data: atmospheric air over the ocean far from the coasts -- $1 \cdot 10^{-18}$,

atmospheric air near the earth's surface -- $1 \cdot 10^{-16}$, and soil air -- $2 \cdot 10^{-15}$, while the content of thoron (a gaseous product of thorium) at the earth's surface can vary from $1 \cdot 10^{-18}$ to $1 \cdot 10^{-16}$.

Rocks are subdivided into igneous, sedimentary (formed from sediments at the bottom of seas and oceans), and metamorphic (formed from sedimentary deposits when acted on by excessive pressures and temperatures). Of the igneous rocks, the highest levels of radioactive elements are found in acidic rocks (rich in silica -- SiO_2) -- $3.5 \cdot 10^{-4}\%$ uranium, $1.8 \cdot 10^{-3}\%$ thorium, and so on, and the lowest -- in ultrabasic rocks (lean in silica) -- $3 \cdot 10^{-7}\%$ uranium, $5 \cdot 10^{-7}\%$ thorium, and so on; of the sedimentary rocks, the highest levels of radioactive elements are to be found in clays ($4 \cdot 10^{-4}\%$ uranium, $1.1 \cdot 10^{-3}\%$ thorium, and so on), clayey rock and potassium salts (25-40% potassium), and the lowest -- limestones ($1.4 \cdot 10^{-4}\%$ uranium, $1.8 \cdot 10^{-4}\%$ thorium, and so on), and other residues of evaporation. The content of radioactive elements in metamorphic rocks is intermediate between their content in igneous and sedimentary rocks.

Radioactive elements penetrate from soil into plants. Concentrations of radioactive elements in plants depend on the diverse factors of the composition and origin of soils, type of natural water, species of plant, climate, relief, and so on. The content of uranium in plant ash varies within the range $5 \cdot 10^{-7}$ to $10^{-20}\%$, and from $8 \cdot 10^{-14}\%$ to $9 \cdot 10^{-7}\%$ -- for radium. /24

From plant food, radioactive and other chemical elements enter the organism of animals and man. Therefore the organism of each person contains virtually all the elements in the Periodic System of Mendeleev. True, the concentration of most chemical elements in people are extremely low. Thus, the uranium content in human tissues $1.3 \cdot 10^{-8}\%$, radium -- $4 \cdot 10^{-10}\%$, iodine -- $1.6 \cdot 10^{-5}\%$, copper -- $1 \cdot 10^{-4}\%$, and so on. For a person weighing 70 kg (average weight), the content of these chemical elements is as follows: $9 \cdot 10^{-6}$ g uranium, $2.8 \cdot 10^{-8}$ g radium, 0.011 g iodine, 0.072 g copper, and so on.

6. Searching for Radioactive Ores at the Surface

Methods of air and ground prospecting are used in searching for radioactive ores at the surface. Only hard radiation with energy roughly from 1 Mev and higher can be used as reference lines in measuring the nature of radioactive elements in these investigations. Low-energy lines in the background of scattered radiation are impossible to discriminate in this case. Since uranium has no hard radiation, its determination in rocks can be based only on radium -- in areas where rocks were formed with

undisturbed equilibrium between uranium and radium. The determination of radioactive elements is usually carried out with the lines: 1.76 Mev -- radium, 2.62 Mev -- thorium, and 1.46 Mev -- potassium.

Underlying air methods of prospecting for radioactive ores is the ability of the gamma-radiation of natural radioactive elements to penetrate considerable distances in the air. The path of gamma-radiation from natural radioactive elements in the air, as we know, is several hundreds of meters. This factor -- strictly speaking -- also makes it possible to record the gamma-radiation from rocks at considerable heights from the earth's surface (AN-2, YaK-12, and other airplanes, MI-1, KA-15, and other helicopters).

In air prospecting, together with radiometric investigations, measurements are made of the earth's magnetic field. This is because the results of combined investigations are used not only in finding radioactive ores, but also in the geological mapping of rock and in searching for other kinds of minerals.

The spectrum of gamma-radiation obtained when measurements are taken from aircraft at elevations of 25-100 m above a homogeneous extended stretch of the ground, using a thallium-activated sodium iodide crystal, 12x8 cm in size, is shown in Fig. 2.6. In this figure we can discriminate the lines 1.76 and 2.2 Mev (radium), 2.6 Mev (thorium), and 1.46 Mev (potassium). At the present time, devices containing six 27x10 cm crystals are used in aerial radiometers. One of the crystals serve to make allowance for the cosmic background, which is automatically subtracted from the readings of the remaining detectors. The results obtained are interpreted with computers and in the form of concentrations of radium (or uranium), thorium, and potassium are entered onto diagrammed tape.

Since the equipment used has considerable inertia, anomalies /26 in aerogamma-prospecting are usually displaced 0.5-1 km in the direction of the prospecting flight line. Subsequent tie-in of the anomalies is carried out using ground forms of prospecting. If the location favors vehicular transportation, the investigations are conducted with motor vehicle prospecting. But if the location is impassable to vehicles, the tie-in of anomalies is done with ambulatory prospecting. This kind of prospecting is also used when tie-in of anomalies of vehicular prospecting is carried out. Each of these methods can also be used independently.

By means of all the above-considered kinds of prospecting, the content of radioactive elements in rock can be determined, beginning with their mean concentrations, shown at the beginning of Section 4 of this chapter.

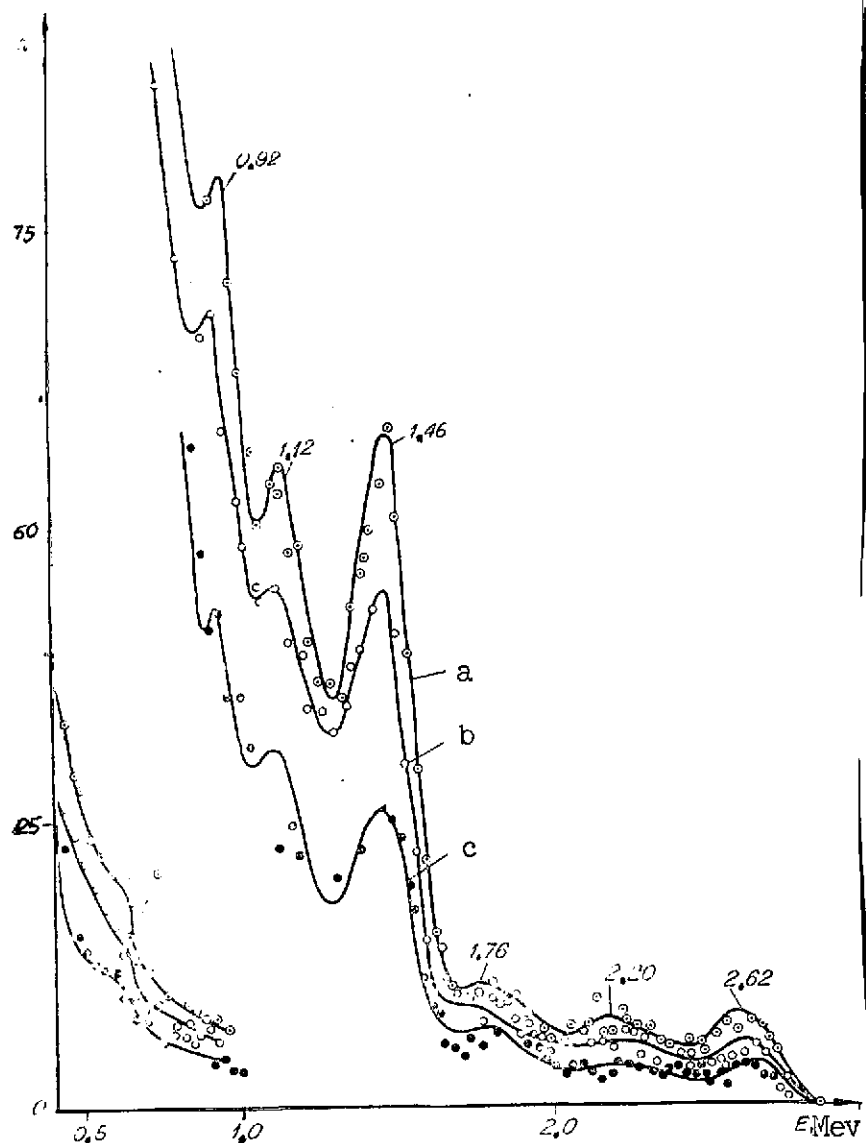


Fig. 2.6. Spectra of gamma-radiation measured at different heights above the surface of homogeneous granites
(N = counting rate, rel. units)
a -- h = 25 m b -- h = 50 m c -- h = 100 m

When ambulatory measurements of beta- and gamma-radiation are taken, the content of uranium and radium in rocks can be determined separately.

Usually the instrument readings are affected by gamma-radiation to depths of not more than 50 cm. To search for radioactive ores lying beneath a layer of loose deposits, lately gamma-plow prospecting has begun to be resorted to. A special plow bearing gamma-radiation detectors is drawn with two tractors and the detectors are allowed to sink to depths of 1-1.7 m.

To study benthic deposits in the water of seas and so on, marine prospecting is used. Here the detector is immersed at the bottom and is drawn behind a ship; the instrument readings are recorded on diagrammed tape.

7. Depth Methods of Searching for Radioactive Ores

At the present time, the surface of nearly the entire Earth has well nigh been studied. Various depth methods are available for searching for radioactive ores at depths. Initially, loose deposits are studied using so-called emanation prospecting -- measuring radioactive gases (radon and thoron).

A blasthole up to 1.5 m in depth is drilled into the ground. Then a hollow probe connected to the instrument with a flexible hose is inserted into the blasthole. Using a special pump built into the device, soil air is pumped into the chamber of the device, in which then its radioactivity is measured. Owing to the low capacity of emanation prospecting, recently it has come to be replaced with gamma-prospecting in blastholes. In particular, this is favored by the introduction into geophysics of devices with scintillation counters and gamma-spectrometers.

Later, by employing hydraulic pressurizers, natural radioactivity began to be measured in pumps with up to 2 m capacity. When self-driven SVA-2 vibro-units were developed, the investigations were conducted in deposits 2 to 5 m deep. At greater depths, investigations of natural gamma-activity of loose deposits are conducted using self-driven SUGP-10 depth-prospecting devices (see Section 8, Chapter Four), employed as well in studying the density properties of soil and in determining their moisture content. Using ground and underwater devices, these investigations of soil properties are made at depths not greater than 25 m. At greater depths, searching and prospecting for radioactive and other kinds of minerals are carried out by drilling blastholes and then studying them with gamma well-logging and other techniques. The contents of radioactive elements can be determined by working with gamma-spectrometers, also beginning with mean content values in rocks.

In conclusion, we note that radiometric methods are used not only in searching for radioactive ores, but also for their prospecting, exploitation, and beneficiation. The latter three applications are called mining radiometry. Its goals include: discovery, contouring, and verification of ore bodies in a massif; monitoring the extraction technology (recording losses and the exhaustion of ores, and controlling these factors in excavation and hauling); evaluating the quality of the crushed rock-ore, its grading, beneficiation, and so on.

8. Predicting Earthquakes

Mankind has long been fascinated with the idea of predicting earthquakes. In Japan goldfish are raised for this purpose: not long before an earthquake the goldfish began to show anxiety. Various animals also show discomfort before earthquakes (dogs, horses, and so on). In Indonesia the activity of volcanoes is evaluated from the behavior of a delicate flower -- the royal primrose, growing on the slopes of volcanoes. This primrose has an amazing ability -- it flowers before the start of a volcanic eruption. Not one case has been recorded when its flowering was not associated with volcanic activity. Thus, fishes, animals, and primroses warn people about a danger threatening them.

Geophysicists conducting investigations in seismically active regions have long sought to develop devices that would give people alarm signals ahead of time. However, crafty nature reluctantly surrenders her secrets to scientists. Still, inquisitive investigators have torn from her one secret after another.

Recently Uzbekistan scientists B. Z. Mavashev and V. I. Ulomov and, independently of them, Kirgizia geophysicist I. A. Luchin directed attention to the fact that before the beginning of earthquakes elastic deformations arise in rocks, leading to the decomposition of minerals. As a result, in the pores of rocks radon begins appearing intensively -- a gaseous product of uranium-radium decay. Along capillaries present in the rocks, radon moves toward the surface of the earth and enters water-bearing strata. In Tashkent this stratum is at a depth of 1.3-2.4 km. /28
The water has therapeutic properties and is extracted through a well. Radon has long since been determined in this water. Before the beginning of an earthquake an abrupt rise in the emanations of water samples was observed (Fig. 2.7 a). During an earthquake capillaries through which water enters the stratum were disrupted and the admission of emanation fell sharply. Similar effects were recorded during and after the earthquake that occurred in Tashkent in March 1967 (Fig. 2.7 b), and in Tyupskiy Rayon, Kirgiz SSR near the city of Przheval'sk, and in Dagestan ASSR.

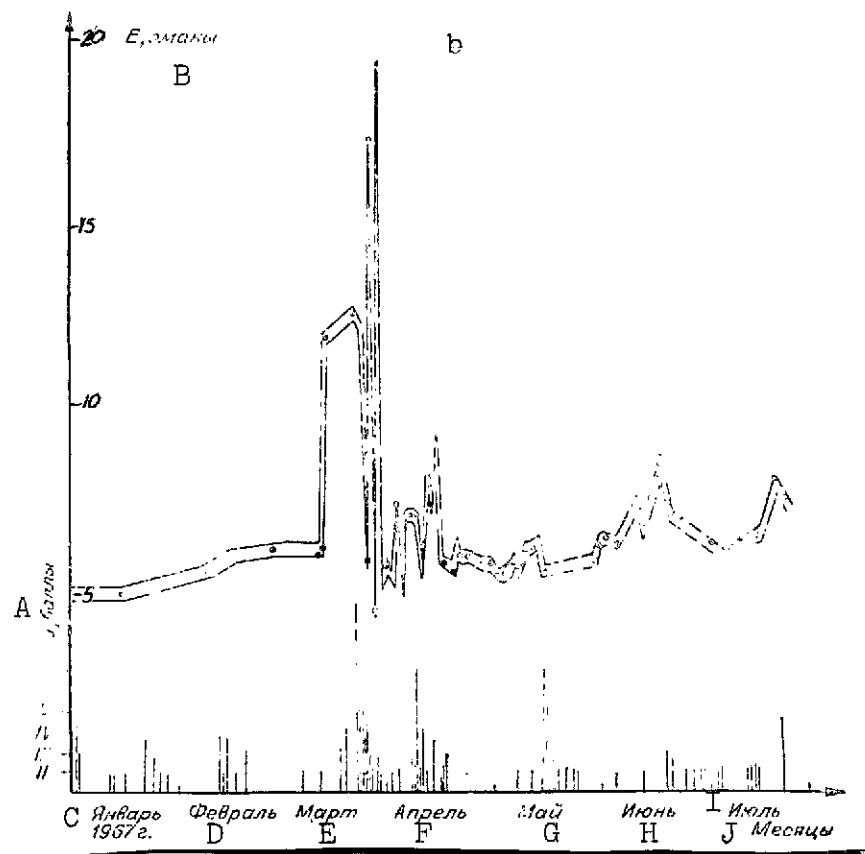
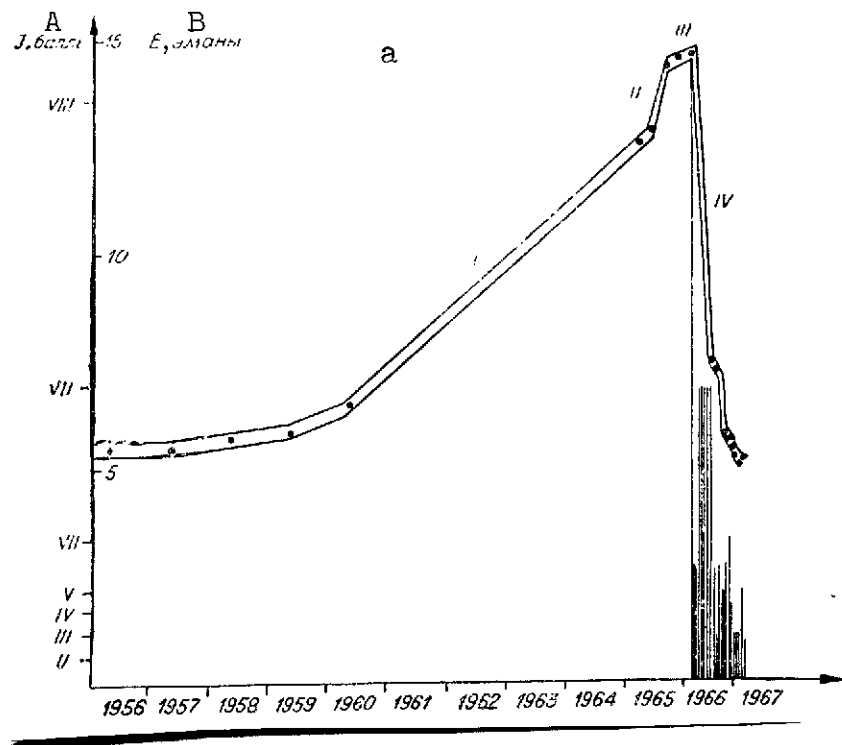


Fig. 2.7. Time variation in concentration of radon in thermomineral water of the Tashkent mineral basin (points in interval between curve) compared with the intensity of subterranean bursts (vertical lines), according to V. I. Ulomyy (a -- 1956-1967 period, different deformation stages are marked with Roman numerals along the curve; b -- period from January to July 1967)

KEY: A. scale divisions E. March I. July
 B. emans F. April J. Months
 C. January 1967 G. May
 D. February H. June

Before an earthquake, groundwater is enriched not only with radon, but also helium, argon, uranium, and other elements. Detailed investigations in this direction were conducted by a group of scientists from Tashkent and Moscow institutes: geophysicists V. I. Ulomov, B. Z. Mavashev, L. B. Gorbushina, V. T. Tyminskiy, and A. I. Spiridonov, by hydrogeologists G. A. Mavlyanov, A. N. Sultankhadzhayev, and L. A. Khasanova, and by geochemist N. I. Khitarov. The Committee on Inventions and Discoveries, USSR Council of Ministers, using materials from these scientists, characterized 12 June 1973 as a discovery making a vast contribution to world science. /29

Azerbaijani scientists established that, moreover, before earth tremors a slight rise in rock radioactivity was observed. This phenomenon is also associated with the incursion of radon into surface deposits. The decay of radon here leads to the formation of new radioactive isotopes that are strong gamma-irradiators.

These methods naturally are not determining in developing techniques of predicting earthquakes under the most diverse geological conditions. To solve this problem, a whole series of other geophysical and geological methods is resorted to. Thus, F. R. Gordon noted that 1.5 hours before the start of an earthquake in a region he studied the water level rose by several tens of centimeters. This also can serve as a precursor of earthquakes.

9. Nuclear Arrivals From Space

/30

The upper layers of the earth atmosphere are continually acted on by cosmic radiation. Even at the dawn of atomic nuclear physics, scientists began studying cosmic radiation. The first investigations were conducted at sea level and on the slopes and summits of high mountains. This mainly dealt with secondary particles arising when primary cosmic radiation acts on the nuclei of atoms in the upper layers of the earth atmosphere.

The upper atmospheric layers became accessible to investigators only with the launching of rockets and artificial satellites. By the launch of artificial earth satellites it was possible to bring the equipment beyond the earth atmosphere and begin studying cosmic radiation outside the sphere of action of the earth's magnetic field. Through comprehensive investigations, it was established that cosmic radiation reaching the upper atmospheric layers consists mainly of protons (~85%) and of particles (~15%). The energy of these particles varies from 10^3 to 10^4 Mev, and the beams vary from about 0.01 (equator) to 0.3 (pole) particle size $\text{cm}^2 \cdot \text{sec} \cdot \text{ster}$. In addition to protons

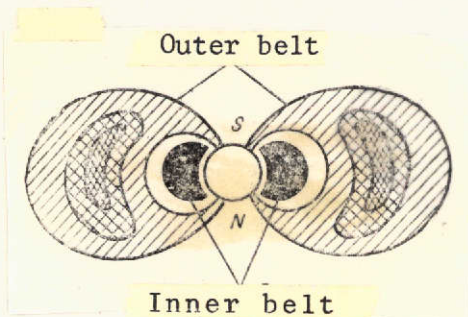


Fig. 2.8. General pattern of distribution of radiation belts around the Earth (density of hatching gives a qualitative idea of the intensity in the outer radiation belt)

and alpha-particles, cosmic radiation contains in negligible amounts atomic nuclei of other chemical elements with atomic number usually not higher than 50 (tin), and neutron radiation. During solar flares, the neutron fluxes can exceed the above-indicated fluxes of charged particles.

Under the effect of fluxes of charged particles, radiation belts form around the earth: the inner and outer belts discovered with satellites and space rockets. Particle fluxes in these belts exceed the normal flux of cosmic radiation by a factor of 100 million. The position of the belts around the earth is shown in Fig. 2.8. This belt distribution is associated with the geomagnetic

and the electrical fields of the earth. The inner belt consists of protons with energies of the order of 10-100 Mev, a flux of $2 \cdot 10^4$ particles/cm²·sec, and electrons with energies from 30 kev to 4 Mev; 99% of the electrons have energy not less than 600 kev and a flux of 10^5 - 10^6 electrons/cm²·sec. The outer belts consists of electrons with energies $n \cdot 10^4$ ev; fluxes of these electrons do not exceed $2 \cdot 10^7$ particles/cm²·sec. Recently, after more detailed investigations of the belt, they were found to be asymmetric. Flattening of the belts was observed from the daylight side, and elongation of the belts from the night side. The region of the maximum for electrons with energy less than 100 kev proved to be weakly defined, while in contrast, the intensity maximum was observed in this region for protons with energy ~ 1 -2 Mev. It was also found that radiation in the inner belt is virtually unchanged, while in the outer belt radiation changes with time both in intensity and in position in space.

The interaction of high-energetic radiation with atoms of the earth atmosphere leads, as remarked above, to the initiation of secondary radiation of complex composition. Here also are generated neutrons forming in their decay the inner proton belt. The deceleration of low-energetic electrons by the atoms in the upper layers leads to the appearance of soft X-ray radiation, which is absorbed in the upper regions of the atmosphere and does not reach the earth's surface.

The earth's surface is reached mainly only by secondary radiation (caused by high-energetic particles), which is subdivided into soft and hard components. The soft component consists of electrons, positrons, and photons, and is similar

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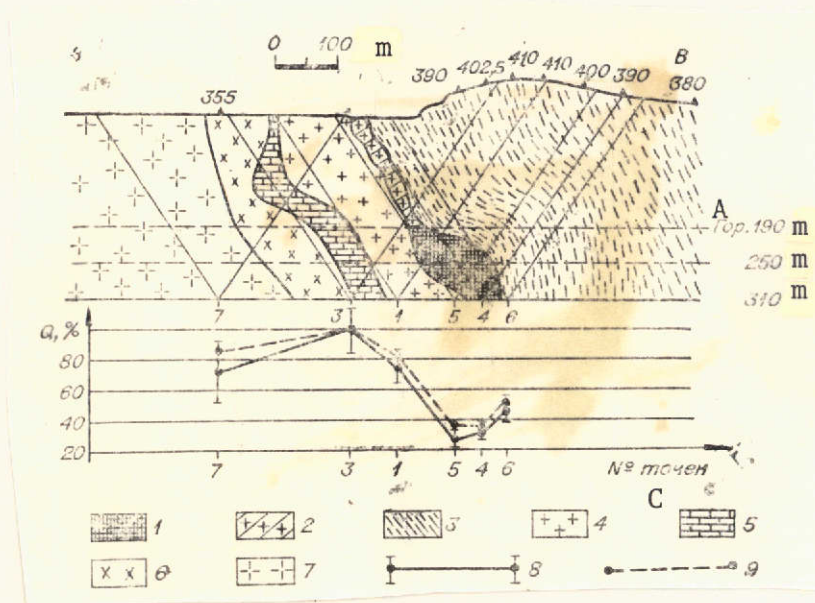


Fig. 2.9. Geological profile and curves of cosmic radiation along profiles across copper pyrite deposit:

1. ore body (4.58 g/cm^3)
2. cave-in zone
3. quartz-sericite shale (3.27 g/cm^3)
4. quartz-albite porphyroids (2.74 g/cm^3)
5. limestones
- 6 and 7. varieties of porphyrites
- 8 and 9. observed and calculated curves of cosmic ray intensity

KEY: A. Horizon C. Point number

in penetrating ability to the gamma-radiation of radioactive elements, while the hard component consists mainly of mu-mesons and has high penetrating ability.

At sea level, cosmic ray intensity is about 1.45 particles/cm²·min, which corresponds to ion formation of about 1.9 ion pair/cm³·sec. With altitude, the intensity of ionization rises under the effect of cosmic radiation.

The hard component of cosmic radiation, owing to its high penetrating ability compared with the radiation of natural radioactive elements can be detected at depth up to 3 km below the earth's surface. By recording this cosmic radiation in underground mines and in boreholes using radiometer-telescopes, one can judge the overlying burden of rock: its thickness and density. Here ore bodies can be detected, differing in density from intervening rock -- karst caverns, fragmentation zones, and so on. As an illustration of the application of this method,

we present data on the detection of ore bodies under the rock (Fig. 2.9): the ore body is revealed by minimum, while limestone by maximum values of the record radiation.

Archeologists have begun to use this method in studying the pyramids in order to discover cavities therein, and so on.

10. Gamma-quanta Unearth Secrets of Moon Rocks

The absence of atmosphere on the Moon made it possible to record gamma-radiation in the upper rock layer directly from lunar satellite orbit. These investigations were conducted first in April 1966 after the launch of 3 April 1966 into lunar orbit of the Luna-10 satellite. The minimum separation of the satellite from the Moon was 350 km, the maximum 1015 km. The gamma radiation was measured with a 32-channel analyzer. The gamma-radiation spectrum was measured in two ranges: a) 0.15 to 1.5 Mev, and b) 0.3 to 3.1 Mev. The ranges were switched on by radio command from earth to lunar station.

Before being sent into space flight, the apparatus must be calibrated in earth conditions. Based on data obtained, the gamma-radiation spectrum was calculated for various rocks of terrestrial origin containing different concentrations of radioactive elements corresponding to the main types of rock (Fig. 2.10).

Lack of atmosphere on the Moon leads to its surface being continually bombarded with beams of cosmic particles (see preceding section). Under the effect of this radiation at the nuclei of atoms of lunar rock, radioactive isotopes of cosmic origin are continually being formed. Therefore the detector readings, in addition to radiation of radioactive elements, are continuously being acted on by the radiation of the isotopes being activated. The gamma-spectrometer used in Luna-10 was capable of separately determining this and other kinds of lunar rock radioactivity.

Based on investigations, it was established that changes in the gamma field at the lunar surface do not exceed 40%. The mean gamma radiation dose at the surface of lunar rock varies in the range 20-30 microroentgen/hr. This is about 1.5-2.0 times higher than the dose above granites of terrestrial origin (14 microroentgen/hr). Such a high radioactivity of lunar rock is mainly due to gamma-radiation of cosmogonic isotopes in the lunar surface. /33

From these results and from a comparison with data in Fig. 2.10, it was established that the lunar surface is formed mainly of rocks of basic (basaltic) and ultrabasic (dunite or chondrite) composition. The first of these is associated with the lunar

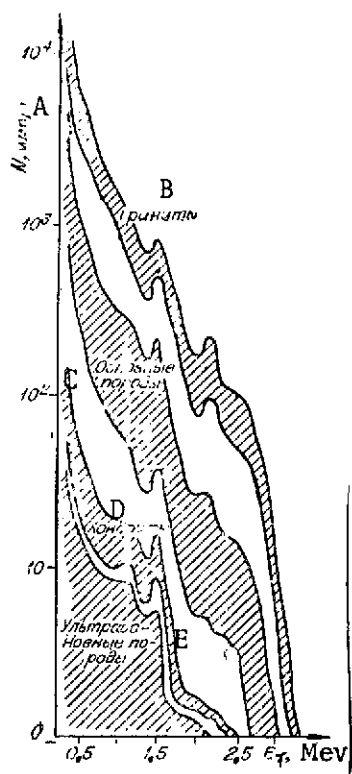


Fig. 2.10. Hypothetical gamma-spectra of lunar rocks that should have been obtained at the orbit of the Luna satellite at the altitude of 350 km (background has been subtracted); hatching indicates the range of concentration of natural radioactive elements for the given type of rock

KEY: A. pulses/hr
B. Granites
C. Basic rock
D. Chondrites
E. Ultrabasic rock

"seas", and the second -- with the "highlands". The content of natural radioactive elements determined from the above-presented method is found to be lower than in tektites (glassy spheres of cosmic origin).

The data obtained are in complete agreement with the data from analyzing rock samples brought to earth by the crews of Apollo 11, Apollo 12, by Luna-16, and so on.

11. Gamma Radiation in the Exploration of the Secrets of Venus

Venus is one of our nearest planet neighbors. It is much closer to the Sun than is the earth. Thus, the mean distance of Venus from the Sun is about 100 million km, while from earth to the Sun -- about 150 million km. Another neighbor is Mars, about 230 million km from the Sun. The Venus-earth distance varies from 40 to 260 million km, while the Mars-earth distance -- 55 to 400 million km. These planets, being earth's closest neighbors, are also after the Sun the priority objects for investigation from space stations.

Spacecraft can reach the Moon, about 380,000 km from the earth, in three days. It takes about 4 and 6 months, respectively, for them to reach Venus and Mars. Mankind is not yet ready to send cosmonauts on extended trips of 8-12 months, therefore automatic space stations are taking on primary importance in the study of Venus and Mars. Equipping the stations with various apparatus made it possible to acquire a great deal of information about the nearest planets. Via the Venera-8 space station, completing more than 300 million km, on 22 July 1972 an apparatus was landed on the

surface of Venus, on board it there was a gamma-spectrometric transducer capable of measuring gamma radiation of natural radioactive elements contained in the rocks of Venus at the station landing site.

The presence of atmosphere on Venus (97% carbon dioxide gas, about 2% nitrogen, about 1% water vapor, and less than 0.1% oxygen) with a pressure at the surface of the rock 100 times greater than on the earth, did not permit judging the content of radioactive elements in the rocks from measurements taken from the orbital station. Therefore to measure the natural radiation of Venetian rocks the scientists were compelled to land the appropriate equipment on the surface of Venus.

Since the temperature at the surface of Venus is about 500°C, a spectrometric transducer located within the station can record gamma radiation at energies from 0.3 Mev and higher (up to 3 Mev). Radiation with energy less than 0.3 Mev is absorbed in the hermetic hull of the station.

Calibration of the spectrometric transducer was conducted in earth conditions. As we know, data were obtained similar to those shown in Fig. 2.9. From the results of this calibration, the contents of elements were determined in the rocks at the craft landing site in the following amounts (% weight): potassium -- 4, uranium -- $2 \cdot 10^{-4}$, and thorium -- $6.5 \cdot 10^{-4}$. These values correspond to concentrations of radioactive elements in granite type terrestrial rock.

From the reflection of radio waves from the surface layer of Venetian rocks, it was found that their density somewhat less than 1.5 g/cm², that is, close to the density of earth soil.

Spacecraft are also advancing on Mars. Thus, today four Soviet stations, Mars-4, Mars-5, Mars-6, and Mars-7 are rushing toward it. They are studying space along the earth-Mars route. It is proposed that they make an integrated study of Mars from their flight trajectory, from an orbital satellite, and from a landing craft.

12. On the Way to Jupiter

Spacecraft are studying not only the planets close to the earth, but even those remote from it. Thus, on 3 March 1972 American scientists launched the Pioneer 10 space station toward Jupiter. As we know, Jupiter is about 780 million km from the Sun. Thus, at the major oppositions, the minimum distance between earth and Jupiter can be about 600 million km. And even more difficult task was assigned to Pioneer: to reach Jupiter, it must travel about 800 million km, as well as the asteroid belt, through which it must fly for 175 days. Along the flight

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trajectory the station can be acted on by large-mass asteroids with their own gravitational field. A major danger represented also by fine particles capable of riddling the station. However, Pioneer passed through the asteroid belt without incident. On 4 November 1973 it flew past Jupiter at a distance of 130,000 km.

The station was provided with a variety of scientific apparatus, including equipment for study of cosmic radiation. The instruments yielded valuable information about Jupiter. The signal reached earth in 46 minutes.

In 1987 Pioneer will leave the solar system forever. Only in 11 million years can it reach the vicinity of the constellation Taurus. In the event this station comes into the possession of rational creatures of other worlds, on board it they will discover a plaque with the drawing of a man and a woman -- the two most typical earthlings, coordinates of the solar system relative to 14 pulsars known to us, the entire solar system, the route of Pioneer, and the symbol of hydrogen atom, which is the most widely distributed substance in the universe. This in essence is the first letter sent by earthlings into space. It is not known whether it will be received by other rational representatives for the universe. At least, the probability of this event is very low. However, before launching it was even less.

At the present time Pioneer 11, launched 5 April 1973, is heading toward Jupiter.

CHAPTER THREE

EXCITED NUCLEI OF ATOMS

1. How Can Atomic Nuclei Be Excited?

Various nuclear reactions take place under the effect of radioactive radiation. As a result of these reactions, very frequently radioactive isotopes -- excited nuclei of atoms -- are formed. Usually electro-neutral particles -- neutrons, freely penetrating within nuclei, are used as the bullets to excite radioactive nuclei. Radioactive isotopes can be formed by the action of alpha particles (see Chapter Thirteen), and hard gamma radiation, protons, neutrons, deuterons, other particles (see Chapter Seventeen). Under the effect of all these particles, samples become radioactive. By /36 measuring the induced radioactivity of these materials, one can estimate their content of chemical elements entering into the reaction and solve diverse geological problems.

A technique based on exciting radioactive nuclei in a material irradiated by neutrons is called neutron activation analysis (NA).

Other activation methods are also named after the exciting radiation employed. This chapter examines only the potentialities of the NA high technique. However, the method of conducting the analysis for this technique and others is similar in general outline. From the example of measurements based on NA we can become acquainted with the techniques of activation analysis in general.

The entire procedure of studying the content of elements being determined in a substance reduces, first of all, to irradiating it with a neutron flux for the time period t_0 , taken as not longer than 5 half-lives ($5T$); secondly, by shifting the sample that is being activated toward the measurement point in the time t_{in} (interval or intermission) and, thirdly, measuring the induced activity in the time t_{in} , also selected not longer than $5T$.

Determination of the nature of elements entering into nuclear reaction is made by measuring the half-life periods, measuring the energy of gamma radiation or the particles, or a combination of both. Each radioactive isotope usually has a half-life characteristic of it, and a characteristic energy of emitted particles. These distinguishing features of isotopes are then used to establish their nature.

The technique of neutron activation analysis is widely used in nuclear physical investigations of geological samples. Radioisotope neutron sources are used for these purposes, along with the radiation of neutron reactors and neutron multipliers. In addition, radioisotope neutron sources are quite widely used in the neutron activation technique in studying rock and ores reached by test wells, and is beginning to be used in study of rocks in the walls of mine workings and rock outcroppings.

2. Excitation of Samples With Neutrons From Radioisotope Sources

Neutron activation analysis was first used by Irving in 1957 (United States) to determine an individual chemical element in geological samples using radioisotope neutron sources. However, the most intense investigation in this direction was started in 1957 by D. I. Leninskaya (USSR). Under her supervision a number of techniques and devices were developed.

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At the present time, single-channel and multi-channel neutron activation units are used in the analysis of geological samples. The design of a single-channel neutron-activation unit and a measuring block is shown in Fig. 3.1. Any vessel can be used in making the activator of this device (a barrel, tank, and so on), about 1 meter in height and about 60 cm in diameter. In the center of this vessel a channel is provided for housing the source and the sample. The sample is secured to the lower part of the cylindrical sample holder. In irradiation with cadmium neutrons, the holder and the sample are moved into a special cadmium jacket.

The induced activity of samples in this device is measured by a scintillation counter. In other similar units, often the induced activity is measured with gas-discharge counters.

The layout of the three-channel activator in series production for the analysis of geological samples is shown in Fig. 3.2. The paraffin moderator is made in the form of a spherical block. In the center of the block is a second, smaller block in cube form. The neutron source is in the center of the cube; it is surrounded by a layer of lead scatterer. Within the cube are three channels for activating the samples in flat cassettes: K -- for activation of samples with epicadmium (thermal) neutron; T -- for activation

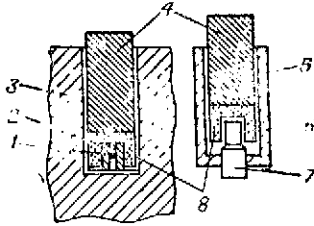


Fig. 3.1. Scheme of one-channel activator (a) and measuring block (b) (after E. V. Anchevskiy and M. A. Belyakov):

1. neutron source
2. intermediate moderator
3. main moderator (water of paraffin)
4. paraffin sample holder of cassette
5. lead housing
6. scintillator
7. cassettes containing samples

irradiators are present in the samples, the measurements are taken with a gamma spectrometer.

Elements with higher sensitivity thresholds can be analyzed by activating them in the channels of neutron multipliers and nuclear reactors.

3. Neutron Multiplier and Its Use in Sample Excitation

In the USSR, the Razmnozhitel-1 activation device has been developed and it is in series production for activation analysis of geological samples, process samples, and activation analysis based on the neutron multiplier. This unit consists of the following main assemblies: PS-1 neutron multiplier (subcritical system); a pneumatic system for conveying the samples into the irradiation zone and into the measurement and storage position; a control panel for the multiplier and the rabbit; and transducers for measuring the induced activity of the irradiated samples.

The arrangement of the neutron multiplier with its control panel is shown in Fig. 3.3. The neutron multiplier is a small-scale nuclear reactor. The fission reaction of the nuclear fuel in the systems and maintenance of the required neutron flux level

of thermal neutrons; and T -- for activation with mixed neutron flux. Channels K and C are located flush with the lead scatterer. Irradiating samples with epithermal neutrons in channel K is carried out by shifting the sample-containing cassette in the cadmium jacket. Channel T is about 2 cm from the lead scatterer.

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The recording block (not shown in Fig. 3.2) is equipped with two replaceable detectors for measuring beta- and gamma-radiation. During measurements, the counters and the sample are placed in lead housings. To measure the beta-activity of samples, gas discharge counters are used, and in measuring gamma activity -- scintillation counters.

Using ampoule neutron sources, ten chemical elements can be determined with activity thresholds from ~ 0.01 to 1% .

The induced activity of samples in the absence of radiation of interfering isotopes is determined by measuring the total radiation. When interfering

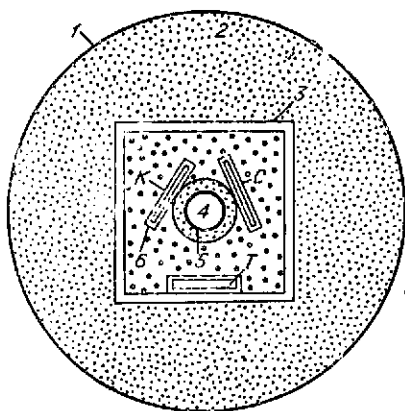


Fig. 3.2. Scheme of three-channel activator (according to D. I. Ley-punskaya et al.):

1. body
2. paraffin
3. internal plexiglas body
4. neutron source
5. lead scatterer
6. cadmium
- T. channel for activation with thermal neutrons
- K. channel for activation with predominantly fast neutrons
- C. channel for activation with mixed neutron flux

neutron fluxes in the multiplier are monitored.

The biological shielding of the multiplier consists of separate removable cylindrical and disk-shaped blocks of lead, boron-containing paraffin, and water.

The presence of the core in the unit makes it possible to increase by roughly 1000 times the flux of neutrons from the radioactive neutron isotope placed in the moderator. The flux of thermal neutrons in the channels is about $1.2 \cdot 10^7$ neutrons/cm²·sec. The fast neutron fluxes in these devices are about three times stronger than the thermal neutron fluxes.

This Razmnozhitel-1 device is intended for placement in a stationary laboratory. Multipliers of the SO-1 and NR-1 models are intended for placement in a truck body. Before hauling these multipliers, the water is poured off and on arrival at the location of the study, the water is added again.

are possible only with an external neutron source. Plutonium-238 -- a beryllium preparation -- serves as this source in the installation described. The long half-life of this isotope ($T = 86.9$ years) makes it possible to maintain in the core a stable neutron flux for the lengthy time of its operation. The source is located in the central channel of the multiplier. In the working position, the source is placed in the center of the core. In order to shut down the multiplier, the source is shifted into the low position by means of a servo drive (into boron-containing paraffin). An absorbing rod of cadmium or boron is located in the core region at this point.

The core is divided into separate disks consisting of powdered uranium dioxide, uniformly distributed in polyethylene and enriched with up to 36% uranium-235 isotope. Around this zone lies a combination neutron reflector, assembled of polyethylene-graphite rods and disks. Three vertical and one horizontal channels are situated in this zone, intended for housing samples. Also, the multiplier houses two more vertical channels. These channels are intended for housing ionization chambers. With them, the

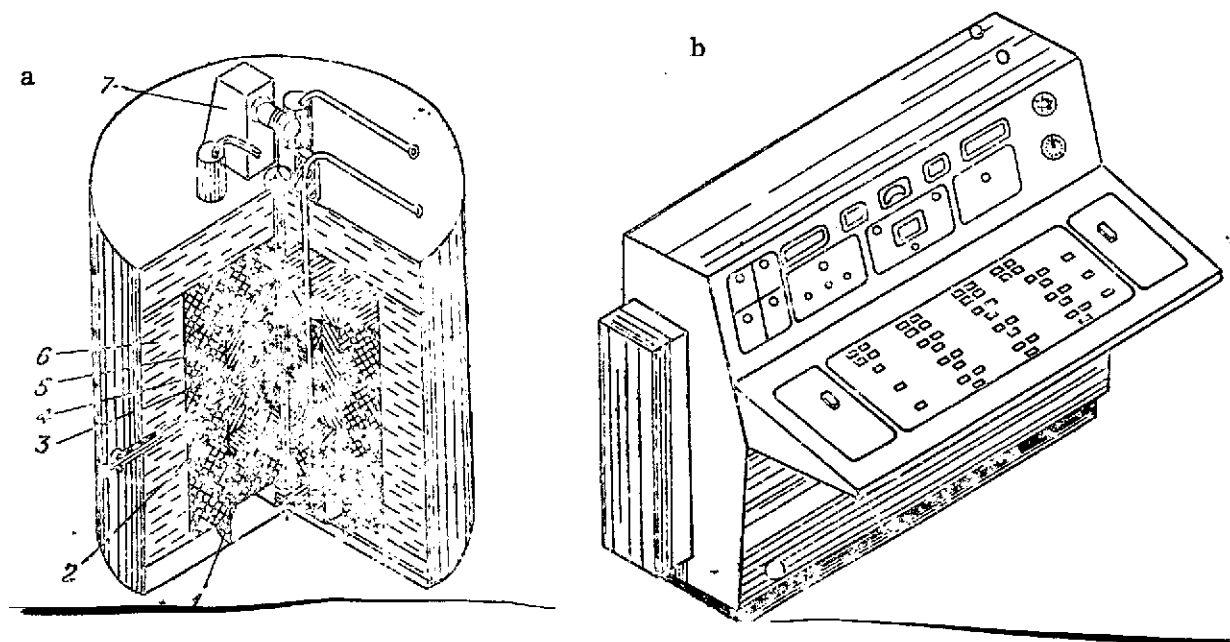


Fig. 3.3. Scheme of design of PS-1 model neutron multiplier (a) and control panel for its operation (b):

1. radioisotope source of neutrons with yield of $2.3 \cdot 10^8$ neutrons/sec
2. core 3. combination neutron reflector 4. lead shielding
5. boron-containing paraffin 6. water shielding 7. servo drive

Similar kinds of devices have been built in the United States and Canada. However, the neutrons in them are produced exclusively through the use of large amounts of radioactive preparations. Thus, the core in a device built in the United States consists of the isotope curium-242 ($T = 163$ days), with an activity of 4000 curies, mixed with beryllium. This device is capable of producing fast neutron fluxes of $9 \cdot 10^7$ neutrons/cm².sec. The core in a unit built in Canada consists of the isotope antimony-124 ($T = 60$ days), with an activity of 6000 curies, mixed with beryllium. Fluxes of thermal neutrons with $2 \cdot 10^8$ neutrons/cm².sec can be produced in the device. In the first of these devices, neutrons are produced via a (α , n) reaction, and in the second -- via a (γ , n) reaction. Both devices have a key disadvantage compared with the PS-1, namely: their use of short-lived isotopes results in the amount of radioactive isotopes in the core decreasing with time. Thus also the neutron yield drops off. The PS-1 unit can be regarded as virtually perpetual from this point of view.

About 40 chemical elements with sensitivity threshold $1 \cdot 10^{-7}$ to $1 \cdot 10^{-2}\%$ can be determined with the Razmnozhitel-1 device.

4. Nuclear Reactor and Use of Its Radiation in Sample Excitation

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As already noted, the first nuclear (atomic) reactor was developed in the United States in December 1942 under the supervision of E. Fermi. Similar investigations were conducted in the USSR by a group of scientists headed by I. V. Kurchatov, and the first nuclear reaction in our country was commissioned in December 1946. At the present time reactors of the most varied types have been built. Nuclear reactors are critical systems. During operation, a self-sustained control reaction occurs in them. Fig. 3.4 gives a schematic representation of the simplest uranium-graphite reactor. The reactor begins to operate after control rods made of boron or cadmium have been drawn from it. Experimental channels in this reactor are intended for the exiting of neutron fluxes. The reactor has built into it special channels within the core for the irradiation of samples. The channel with the rabbit is intended for investigations with short-lived isotopes.

Neutron fluxes in reactors, depending on their type, can be of different intensities. In low-power reactors, fluxes of thermal and fast neutrons up to 10^{10} - 10^{11} neutrons/cm².sec are produced, and in more powerful reactors -- up to 10^{12} - 10^{15} neutrons/cm².sec. A special-purpose RG-1 nuclear reactor containing uranium dioxide enriched with 10% uranium-235 was developed in the USSR for activation analysis of geological samples. The reactor is provided with 11 channels, two of which are equipped with a rabbit. One of these channels has a cadmium shield and provides for activation with epithermal neutrons. The rabbit makes it possible to

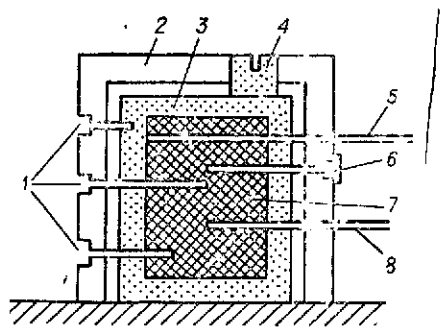


Fig. 3.4. Schematic cross-section of uranium-graphite reactor:

1. experimental channels
2. shielding
3. graphite reflector
4. thermal column
5. control rod
6. enclosed channel for irradiating samples
7. uranium-graphite lattice
8. channel containing pneumatic rabbit

transport samples weighing up to 50 g at speeds up to 10 m/sec. Fluxes from $2 \cdot 10^{10}$ to $9.3 \cdot 10^{10}$ neutrons/cm²·sec can be produced in the thermal channels. A special room is designed for housing the nuclear reactor./

Extremely intense neutron fluxes can be produced in the IIN-3, IGR, and other pulsed reactors. The IIN-3 reactor functions in both the steady as well as in the pulsed regime (Fig. 3.5). Twenty-three liters uranyl sulfate is poured into the internal cylindrical cavity of the housing. In this core, the uranium is enriched with up to 90% uranium-235. The and control rods are made of /42 boron carbide. The reactor is introduced into the working regime by the rapid removal of the start-up rod from the core with a pneumatic drive. When this is done, the liquid seemingly boils up and

leaves the limits of the working zone. If after the flareup control rods are not inserted into the reactor (by means of electromechanical drive), it operates in the steady-state regime. In this case, a flux density of $1 \cdot 10^{12}$ neutrons/cm²·sec is produced in the experimental channel, and $2 \cdot 10^{11}$ neutrons/cm²·sec at the surface of the housing. When the reactor is operating in the pulsed regime, a flux density of about $8 \cdot 10^{14}$ neutrons/cm²·sec is produced in the central channel, and $1.5 \cdot 10^{14}$ at the surface of the housing.

These reactors are advantageous to operate in the pulsed regime when activating short-lived isotopes. Thus, when samples are activated in the IGR reactor producing a flux density of $1 \cdot 10^{18}$ neutrons/cm²·sec, when isotopes are formed with a half life of about 1 sec, their activity rises by 35 times compared to irradiation in a reactor operating in the steady-state regime.

Using the thermal neutron radiation of nuclear reactors, the vast majority of chemical elements in the periodic system can be activated and analyzed with a high sensitivity threshold. Of the 84 stable elements and the two radioactive elements with a long half-life (uranium and thorium), 74 can be determined by

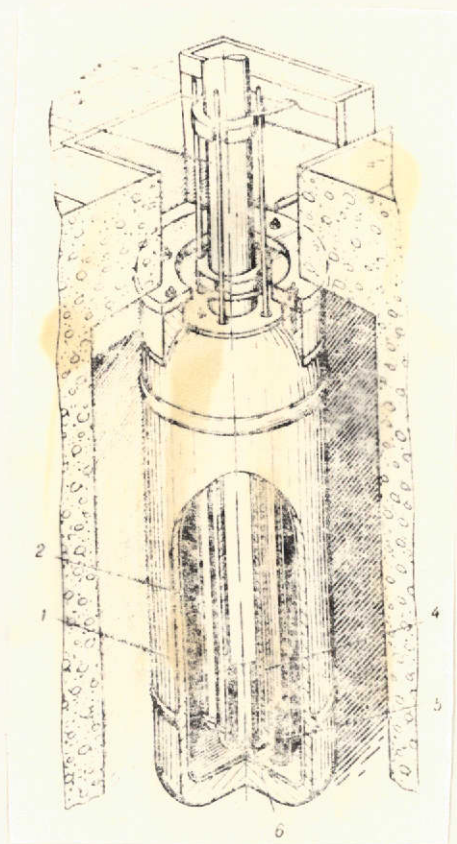


Fig. 3.5. Layout of IIN-3 nuclear reactor:

1. body of reactor with inside diameter 39.2 cm
2. channels of absorber rods (four)
3. cylinder of pneumatic drive
4. cylindrical startup rod with outside diameter of 9.6 cm
5. control rods (four)
6. central experimental channel, 7.5 cm in diameter

cm².sec). The sensitivity threshold here can be 10^{-7} g. The remaining 69 elements, activated by thermal neutrons, are quite easily determined when activated in reactors with mean fluxes of (10^{11} - 10^{13} neutrons/cm².sec). Thus, the RG-1 reactor can be used for determining 44 chemical elements in rocks and ores.

activation with thermal neutrons. This method is unfavorable for determining the 10 lightest elements -- hydrogen, helium, lithium, beryllium, boron, carbon, nitrogen, oxygen, fluorine, and neon. Eight of these elements have extremely low thermal neutron capture cross sections (less than 1 mbarn), except for boron and lithium. Some of them have very short (oxygen, fluorine, nitrogen, neon, and boron), and some very long (lithium, hydrogen, helium, carbon, and beryllium) half-lives of the radioactive isotopes induced.

The foregoing concerning elements forming short-lived isotopes is valid if the determining laboratories are located far from reactors. If the laboratories are close to a reactor and are in contact with it by means of rabbit, the elements oxygen, fluorine, nitrogen, neon, and boron can be analyzed by fast neutron activation. In this case, the reactors can be used in analyzing 78 elements.

The technique involving thermal neutron activation is poorly suited for determining sulfur, zirconium, calcium, iron, and lead owing to their low activation cross sections and their long half-life. They are convenient to determine only after being activated in strong fluxes (10^{14} neutrons/

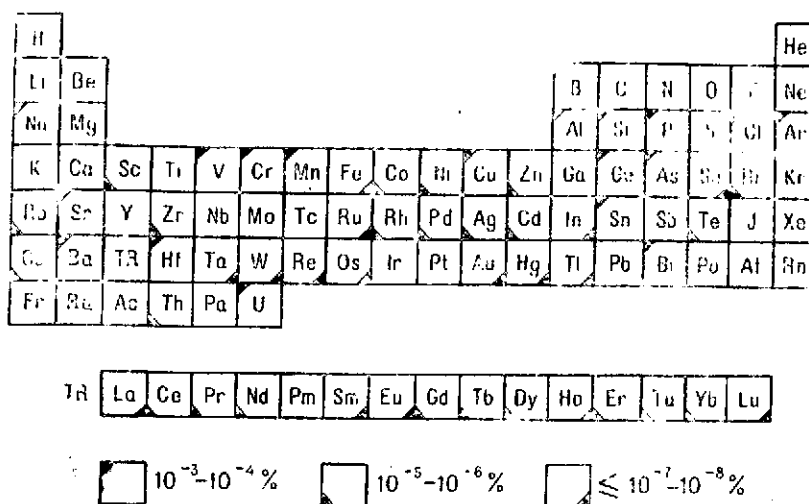


Fig. 3.6. Sensitivity thresholds in the determination of several elements in geological samples upon irradiation in nuclear reactors

The possibility of determining 57 chemical elements in geological samples using nuclear reactor radiation can be evaluated from the data in Fig. 3.6. Most of the elements shown are determined instrumentally without chemical breakdown of the rock sample. However, the highest sensitivity thresholds are achieved in activation analysis involving radiochemical separation.

Of major interest in measurements based on thermal neutron activation is the use of solution pulsed reactors of the IIN type with fluxes of 10^{14} neutrons/cm² per pulse. With it, a long series of chemical elements can be determined in nature, with sensitivity threshold from 10^{-3} to $1 \cdot 10^{-4}\%$. /44

Nuclear reactors are used not only for activating the nuclei of atoms of chemical elements with neutron fluxes, but also with secondary particles formed in the nuclear reactors -- (n, α) , (n, p) , (n, d) , (n, t) , and so on. Under the effect of the charged particles produced, various nuclear reactions can develop, leading to the formation of radioactive isotopes. By measuring their induced activity, one can analyze diverse chemical elements and their isotopes. Recently, increasing attention is being given to studying the content of various isotopes in geological materials. The solution of this problem as applied to specific chemical elements and their compounds will permit, in the view of geologists, a new approach to questions of the origin of mineral deposits, and so on.

5. Excitation of Nuclei of Atoms of Chemical Elements in Bedrock Deposits of Rock and Ores

The advantage of determining chemical elements directly at the rock bedding is indisputable. It is not surprising that this technique was first used in studying profiles of test wells (1953), and only four years later did it begin to be used in analyzing samples. Lately, several chemical elements at the planar rock surface have come to be determined by this technique -- in ambulatory and vehicular investigations.

The technique of studying test well profiles based on the induced activity of the isotopes produced came to be called neutron activation well-logging. Isotopes with short half-lives (several minutes) can be determined during the travel of the test well device. Isotopes with longer half lives are determined only when the device stops -- point or discrete measurements. To eliminate the effect on the readings of the neutron gamma-radiation detector, a neutron source with a yield of about $1 \cdot 10^7$ neutrons/sec is placed at distances of 1.5-2 m, and sometimes even 3-4 m from the detector.

At the present time, fluorine, aluminum, silicon, manganese, and copper are determined in rocks and ores by this technique.

The fluorine content in rocks is determined by fast neutron activation. When gamma-quanta with energies of 2.5-3 Mev and higher are recorded with scintillation counters, the effect of all interfering radiation can be virtually eliminated and the fluorine content in rocks determined reliably. It is determined along the test well profiles at rates of 400-500 m/hr with a sensitivity threshold of 0.2% and absolute error of 0.04-0.07%. In vehicular prospecting, during the time the instrument is moving (3-4 km/hr), a fluorine sensitivity threshold of 0.08% is achieved, and when the instrument is no longer in motion -- a fluorine sensitivity of 0.03%. In ambulatory measurements, fluorine is determined beginning at 0.05%.

Fluorites (CaF_2) and apatites $[\text{Ca}_{10}(\text{PO}_4)_6(\text{F}, \text{Cl})]$ are discovered by the technique of fluorine activation in rocks. Moreover, phosphorites $[\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2]$ are determined in rocks from the presence of a correlation between fluorine and phosphorus.

Specialists calculate that introducing this technique for discovering fluorites based on test well profiles will mean an annual saving of about 175,00 rubles per instrument.

When silicon is exposed to fast neutrons, and when aluminum is exposed to thermal neutrons, the same radioactive isotope, aluminum-28 is formed. For the separate determination of these elements, it is recommended that the rock be irradiated with two types of

neutron sources: polonium-boron ($E_{ab} = 2.7$ Mev), and a polonium-or plutonium-beryllium source ($E_{av} = 5$ Mev). When rock is irradiated with neutrons from the polonium-boron source, only the nuclei of aluminum atoms are activated. Thus, the content of this element in the rock is established. In this case, silicon can be determined only by the difference technique when two sources with different fast neutron energies are operating. Aluminum and silicon are determined in boreholes at speeds of 30-70 m/hr with an average sensitivity threshold of 5 and 15%, respectively.

Manganese in rock is determined only in point measurements. This is associated with the high half-life of the manganese-56 isotope formed ($T = 2.56$ hr). The manganese content in rock, depending on its material composition, can be determined with a sensitivity threshold of 0.01-0.1%.

The technique of point measurements based on a short-lived isotope -- copper-66 ($T = 5.1$ min), and based on a long-lived isotope copper-64 ($T = 12.8$ hr) is used in determining copper in rock from test well profiles. The copper content in ores is low (0, n-n%), therefore a large number of elements interfere with its determination in rock. When measurements are based on the short-lived isotope, radiation from aluminum-28 ($T = 2.3$ min) and manganese-56 ($T = 2.56$ hr) interfere, and when the determinations are based on the long-lived isotope, manganese-56 and sodium-24 ($T = 15$ hr) interfere. In the event of low content of aluminum and silicon in ores (in aluminum equivalents) and low manganese content, it is recommended that the technique based on the short-lived isotope be used. In the event of high concentrations of these interfering elements, it is recommended that the technique based on the long-lived isotope be employed.

Copper determination based on the short-lived isotope is conducted at a 0.5% sensitivity threshold, and when based on long-lived isotopes -- at a 0.2% sensitivity threshold. The copper content in the walls of mine workings is determined with the same sensitivity threshold.

Neutron activation well-logging is used also for penetrating 46 to water-petroleum contact based on the activation of chlorine and sodium contained in mineralized stratal water. However, after the development of neutron well-logging generators (see Chapter Sixteen) and their introduction into field use, the method lost its significance.

CHAPTER FOUR

NUCLEAR DENSIMETERS

1. Rock Density

As we know, density is one of the most important physical parameters characterizing rocks and soils comprising the Earth and other celestial bodies.

The mean density of the Earth is 5.52 g/cm^3 , and of its upper layer -- the 30 km thick Earth's crust -- 2.8 g/cm^3 . The mean density of the Moon has been estimated at 3.33 g/cm^3 . Until recently nothing was known of the density of individual rocks in the lunar surface. Still, the density of Earth rocks outcropping at the surface varies over wide limits: from $1.5\text{--}1.8 \text{ g/cm}^3$ (soils) to $2.7\text{--}3.2 \text{ g/cm}^3$ (granites, diabase, and so on). The density of ore bodies can reach considerably high values: about 5 g/cm^3 for iron ores, and 7.5 g/cm^3 for lead ores, and so on.

Data on the densities of various rock formations are essential in studying the structure of the Earth and its individual envelopes, and also in searching and prospecting for minerals. Data on soil density are essential in solving engineering-geological problems involved with erecting various structural projects, and so on.

The gravimetric method is the classical technique of determining the density of rocks and soils. For this purpose, a sample of rock is selected, its weight P and volume V are then determined. The ratio of these quantities corresponds to the specific weight (specific gravity) of the sample:

$$\rho = P/V \quad \text{g/cm}^3.$$

Special gravimetric densimeters have been designed for determining the density of rocks. Using these instruments, rock samples are weighed in air and in water, and thus their density is determined.

This method is called hydrostatic weighing in geophysics. When density is determined with a densimeter, pores of rocks must be paraffinized, which complicates the measurement technique.

Here the density of soils is determined with the so-called cutting ring. A ring with a known volume is pressed into soil and from it the ring is extracted together with the cutout soil. Using a cutting device, the soil is levelled off from the edges of the ring. Then after the sample has been weighed, its density is determined in elementary fashion. However, the steps in pressing the ring into the soil and levelling the soil enclosed in the ring lead to its deformation. This in turn results in imprecision in the determination of soil density.

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2. Nuclear "Scales"

The technique of determining the densities of soils and rocks can be appreciably simplified only by using nuclear radiation. The most appropriate for these purposes is gamma rays capable of penetrating through considerable thicknesses of matter. When acting on a substance and, in particular, on rock, gamma rays interact with their electrons. If the energy of the gamma rays is chosen in the range 0.2-1.5 Mev, their attenuation in the material occurs mainly owing to scattering. The phenomenon of gamma ray scattering was discovered by Compton and in honor of his name is called the Compton effect, or Compton scattering. The attenuation of gamma rays in matter by means of this effect is proportional to the number of electrons per unit volume of the matter, which in turn is proportional to the density of the matter. Thus, by irradiating rock with a gamma-ray flux and recording the radiation scattered or passing through the rock, we can estimate its density.

A long series of nuclear "scales" is based on this phenomenon, capable of determining the density of rocks, that is, as if weighing them, and not only using specimens in the laboratory, but right in the field at the site of bedrock outcroppings without taking samples. Here the gamma-radiation sources are the radioisotope sources cobalt-60 and cesium-137, which has half-lives T 5.3 years and 30 years, respectively. The cobalt source emits two gamma-quanta with energies 1.17 and 1.33 Mev, while the cesium source emits gamma-quanta with 0.661 Mev. Upon reacting with the electrons in the material, the gamma-quanta are scattered. The energy of the gamma-quanta becomes less with each scattering act.

Geiger-Muller gas discharge counters or scintillation counters are used to record radiation scattered or passing through a sample.

Densimeters based on recording predominantly primary radiation passing through rock are called transmitting or absorption gamma-densimeter (GD), while densimeters based on irradiating rocks with a flux of primary radiation and recording the scattered radiation are called gamma-gamma-densimeters (GGD).

3. Nuclear "Awl"

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The density of collected rock and soil samples is determined mainly with transmitting GD. A diagram of one such device is shown in Fig. 4.1.

To irradiate a test sample with a narrow beam of gamma-rays, the source and the radiation detector are placed in lead blocks with narrow cylindrical openings (collimators). The source block not only shapes the narrowly-directed gamma-ray beam, but also protects the operator against radiation. The lead block of the detector, besides recording the narrowly directed radiation beam passing through the sample, shields the counter against radiation from extraneous objects, cosmic radiation, and gamma rays leaving the sample and scattered by surrounding objects, and so on. The narrowly-directed gamma ray beam penetrates like a unique "awl" any rock specimen (not more than 10 cm in thickness), without leaving a trace behind.

Gamma rays penetrating a sample and partially scattered by the electrons of the atoms are deviated from the direction of the primary beam and do not arrive at the collimator of the radiation detector. The higher the density of the sample and the greater its thickness at the point of transmission, the smaller the number of gamma rays striking the detector.

The lead block containing the source can be shifted along the frame with a vernier scale. Based on this scale, the thickness of the sample pressed between the apices of cone-shaped lead blocks can be determined to 0.1 mm.

The Siberian Special Design Bureau of Geophysical Instrument-Building, USSR Ministry of Geology, built -- on the basis of this instrument -- a transmitting device for determining the density of rock samples, part of the UGGP-1 universal densimeter set.

By trans-illuminating samples with these devices, one can determine the density at different places and in different directions. Paraffinizing of samples is no longer necessary. The density of samples can be determined with the devices described based on a preconstructed calibration curve, with a relative error of 1%, that is, rocks and ores with densities in the 2-4 g/cm³.

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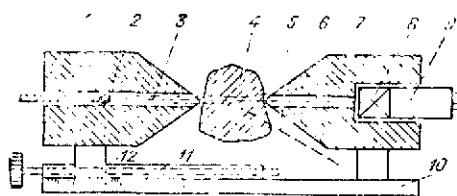


Fig. 4.1. Schematic diagram of gamma-transmitting device used in determining the density of samples of irregularly shaped rock (developed by the Institute of Geology and Geophysics, Siberian Division of the USSR Academy of Sciences):

1. lead shield of source
2. gamma-ray source
3. collimating opening, directing radiation as a narrow beam at the sample
4. test sample
5. radiation leaving the beam due to scattering in the sample
6. radiation reaching the receiving collimator
7. lead shield of receiving block
8. receiving phosphor
9. photomultiplier recording light flashes in phosphor
10. frame
11. reading scale
12. vernier

simultaneously introducing into the medium a pin with source and probe plus detector (Fig. 4.2). Single-pin densimeters can have one detector instead of two at their surface. The pin containing the source is pressed into the soil either at a right angle to the test medium, or at an inclined angle. In all cases the pin is inserted into the soil with a special guide -- a conductor.

range can be determined with an absolute error of $\pm 0.02-0.04$ g/cm³. From 2 to 3 minutes is spent in measuring the sample in one direction.

Simpler devices (without cones and vernier scales, and with rigidly mounted source and detector of blocks) are used in determining the densities of samples with constant thickness, for example, soil, sampled with the cutting ring. When used in studying soils with constant density, these devices can be used in determining the moisture content.

4. Gamma-ray "Weighing" of Soils and Rocks Without Sampling

The technique of determining densities of rocks examined above does have disadvantages. When it is used, samples must be taken and sent to the laboratory. Much time can pass from sampling to measurement of a sample. Still, the high penetrating ability of gamma rays makes it possible to more efficiently resolve the problem of determining the density of soils and rocks directly at their bedding site without taking samples. Special gamma-transmission densimeters were developed for these investigations. The density of friable formations is found by introducing into the test medium a pin containing one source or by

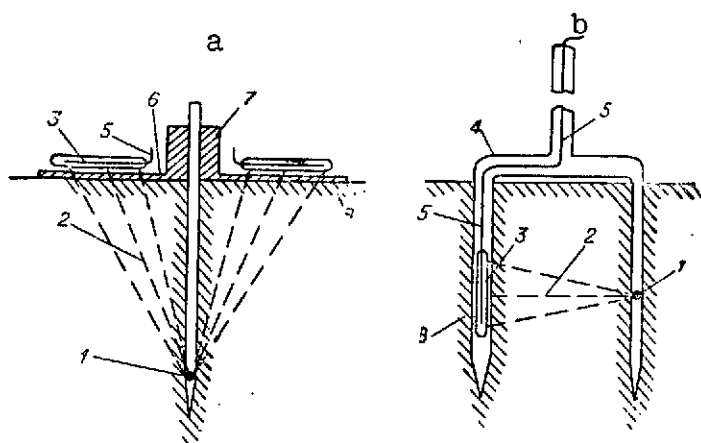


Fig. 4.2. Schematic diagram of field devices for determining the density of soils, ground and other various free-flowing media

- a. device with one embedded radiation source (after I. Wendt)
- b. device with embedded source and radiation detector "radio-active fork" after K. Ye. Krompton.
1. gamma-ray source
2. primary beam of gamma rays directed toward detectors
3. gas-filled gamma-ray detector
4. base of fork
5. cable connecting detectors with radiometer panel
6. plate installed in the soil
7. guide for placing probe containing radioactive source in the soil
8. medium whose density is being determined

The density of ground and soils using gamma-transmission "scales" can be determined at a 1.5 m depth with a relative error of 1-2% in 2-3 minutes. When ground with variable frequency is investigated, these devices are used also in determining their moisture to up to 2% precision.

At the present time gamma-transmission densimeters have also been built for determining the density of liquid in the core of a test well. Petroleum from deep-lying rock is extracted through test wells. The cores of these test wells contain along with aluminum, also water arriving from the water-bearing strata or especially pumped into the test well during its drilling. A 0.2 g/cm³ difference in the densities of petroleum and water can be clearly determined with these instruments.

5. "Weighing" of Rock in Bedrock by Scattered Radiation Flux

When determining the densities of rocks in bedrock, GGD based on recording scattered radiation are most suitable. Insert, probe, and borehole densimeters have been developed on this principle. In order to protect the detector against primary radiation, between it and the source is placed an adequate layer of lead or tungsten.

The calibration graph for a GGD in the form of a curve is shown in Fig. 4.3. With increase in the density of the medium being studied, the rate at which the radiation is recorded initially

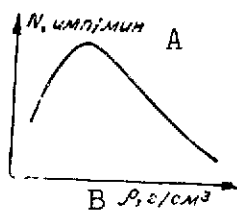


Fig. 4.3. Calibration graph of densimeters based on recording scattered gamma-radiation (ρ is density)
KEY: A. N , pulses/min
B. g/cm^3

risers, and then are reaching a maximum, falls off. The left, ascending, part of the graph is usually used when determining media with densities not higher than $2 g/cm^3$, that is, media such as peat, soil, and ground. The distance between the source and the radiation detector (probe size) here is chosen as small as possible. Since an absorber must be placed between the source and the detector, the probe size must not be chosen smaller than 4-5 cm when using a tungsten shield and a cesium gamma-ray source. The density of

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rocks from $2 g/cm^3$ and higher is determined based on the descending branch of the calibration graph, by choosing the probe length longer than 10 cm.

6. Insert Densimeters

Insert GGD are used in determining the densities of rocks at the location of instrument contact with the medium being examined. A schematic layout of the densimeter transducer with a scintillation counter is shown in Fig. 4.4. Fig. 4.5 is a photograph of a densimeter that is part of the UGGP-1 set. The lead block of the source directs the primary radiation of the cesium source into the rock and protects the radiation detector and the operator from the radiation. The lead layer at the transducer case is necessary for additional protection of the detector from direct gamma radiation of the source. In addition, this shield protects the detector against radiation propagating in the near-surface layer of rock and promotes the recording of radiation from the deep parts of the rock located opposite the detector.

The density of rocks in their bedding site can be determined with the insert densimeter to a relative error of 1-1.5%.

Vehicular densimeters have been designed for determining the densities of rocks while travelling along the specific routes. In transducer layout they are similar to insert densimeters. Blocks containing source and detector in mobile densimeters are placed on special runners hauled by the motor vehicle. The instrument readings during the operation are recorded on special diagrammed tape. The density of the rock can be determined with these densimeters while in motion with a relative error of 2-3%.

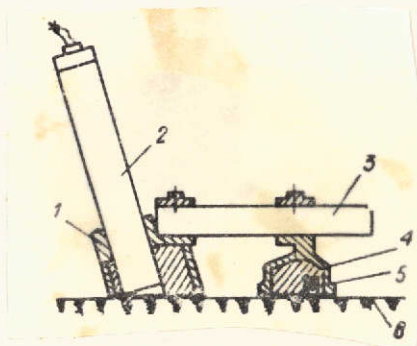


Fig. 4.4. Diagram of transducer of the PGGP-1 insert gamma-gamma densimeter developed in Institute of Geology and Geophysics of the Siberian Division, USSR Academy of Sciences:

1. detector of block (aluminum body filled with lead)
2. case of radiometer containing detector
3. lever acting as a rod connecting the source block with the detector block
4. source block (aluminum body filled with lead)
5. gamma quanta source
6. surface of test medium

7. Lunar Densimeter

In December 1966 an insert type densimeter with gas-discharge counters was brought to the lunar surface on board the automatic space station Luna 13. The use of small scale radiation counters in the densimeter made it possible to build a highly miniaturized device (Fig. 4.6) 25.8 cm in length, 4.8 cm in width, and 1.0 cm in height. It housed a cesium source with an activity of 1 mg.eq. radium, a lead separating shield, and three groups of small-scale gas discharge counters of the SBM-10M type (five in each group). Each group of counters was arranged at different distances from the source in order to weaken the effect of irregularities in the surface measured. The

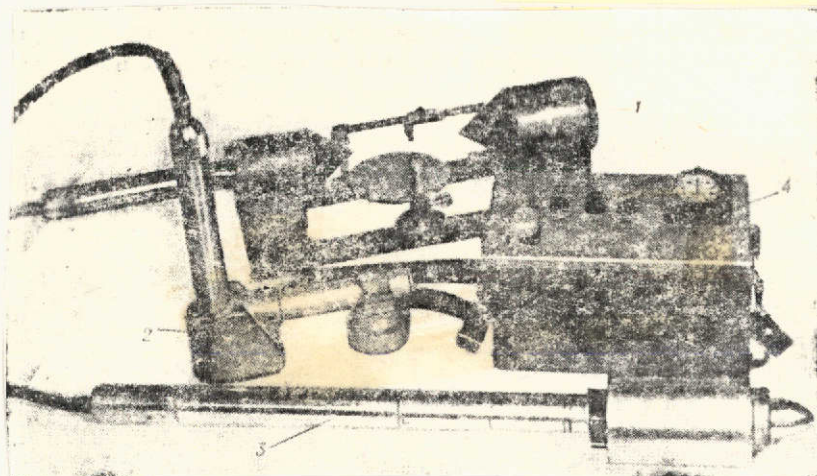


Fig. 4.5. UGGP-1 universal gamma-gamma-densimeter

1. trends-illuminating device for determining density of rock samples
2. insert device of densimeter
3. probe of densimeter with protective shield
4. instrument panel

radiometric part of the device was constructed of transistors. The instrument was calibrated in earth conditions in media with densities from 0.16 to 2.6 g/cm³.

The resulting measurement along the curve corresponded to densities of 0.80 and 2.15 g/cm³ (see Fig. 4.3). The first of these values was taken as the most reliable. This is due to the fact that astronomical, photographic, and radiophysical investigations on the lunar surface did not detect solid rocks. Later, these reports were confirmed by data from an analysis of the density of soil brought back by the spacecraft Luna 16. It was established that the upper 5 cm thick layer has a density of about 0.8 g/cm³, and the mean density of the entire sample returned (a column 35 cm in length) proved to be 1.2 g/cm³. Study of rock samples collected by the crew of Apollo 11 showed that the density of lunar soil is 1.54-1.66 g/cm³, while the density of crystalline and glassy rock is 3.1-3.4 g/cm³.

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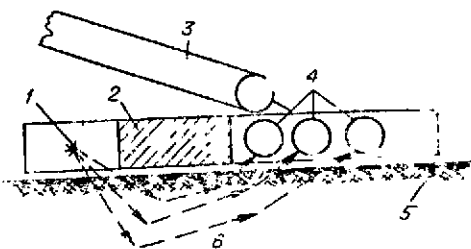


Fig. 4.6. Schematic diagram of insert densimeter landed on the lunar surface:

1. gamma radiation source
2. protective shield
3. mechanism for bringing the densimeter out of the landed craft
4. group of gas discharge counters
5. lunar surface of rocks
6. schematic path of gamma ray from source to detectors

8. Density Probing of Rocks

To determine the density of rocks in drillholes and blastholes, probe GGD have been developed (Figs. 4.5 and 4.7). Radiation leaving the source is scattered by the rock and strikes the detector. From the intensity of this radiation, one determines the densities of rocks in the drillholes or blastholes. The highest precision of measurements (1%) is achieved when there is no gap between probe and rock. Therefore the densimeters considered here found their greatest use in the study of friable deposits: soils, fill structures, underwater benthic deposits, and so on. V. I. Ferronskiy and others built self-propelled land and floating devices for the study of these deposits. The probe was

forced by means of these devices into the medium being studied with the aid of a special system of rods. A schematic diagram of the SUGP-10 self-propelled depth search device is shown in Fig. 4.8. A hydraulic pressuring system is installed on a stock tracked drive vehicle. But the recording equipment is located on a separate GAZ-63 truck. With this unit, the probe can be forced into rocks of the second and third category of strength at a rate of 6.25 m/min.

Recently, new penetrating-well-logging stations have begun to be built for land (SPK type) and underwater (PSPK type) studies.

In the SPK penetrating-well-logging station, the hydraulic system is mounted on the chassis of an increased roadability VIL-157 truck, while the recording equipment is mounted on an increased roadability KAVZ-663 bus. Pressuring of probes by means of this unit can be done at rates of 3.5 or 8 m/min.

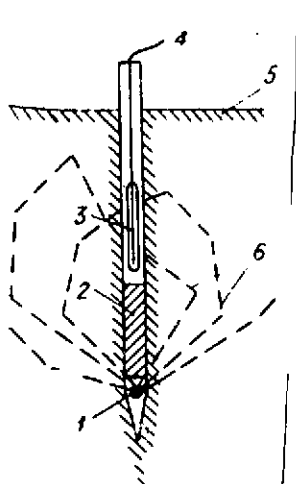


Fig. 4.7. Schematic diagram of probe type gamma-gamma densimeter:

1. gamma-ray source
2. lead shields protecting detector against primary radiation of source
3. gamma-ray detector
4. cable connecting probe to radiometer panel
5. medium whose density is being determined
6. several trajectories of gamma quanta extending from source to detector

The PSPK underwater penetrating-well-logging station is mounted /54 on series-produced KS type pontoons. The main components of this station include an underwater unit intended for pressured immersion of a probe screwed onto the column of penetrating rods, and extracting it; floating equipment with rigging for transporting the device, immersing it at the bottom of the body of water, and recovering it, housing the measuring equipment, device control panel, and electric power source, as well as housing the crew. Probes can be pressured with this device at a rate of 6.25 m/min.

In 1972, the Geolog-1 specialized vessel was designed for this kind of research into benthic deposits. It was provided with the appropriate equipment and can be used not only for engineering-geological investigations, but also for searching and prospecting minerals in the continental shelf zone.

The density of the rock deposits studied can be determined using these densimeters with 40 cm probes to a relative error of 1-1.5%.

The penetration units together with their sets include, besides the density probes, also other nuclear-geophysical probes for integrated investigations, which will be discussed below. Besides the nuclear-geophysical probes, these devices include in their sets probes also for studying rocks based on their mechanical and electrical properties. The combined use of all these probes

will permit a comprehensive study of various physical properties of deposits under study and the prompt adoption of the required decisions.

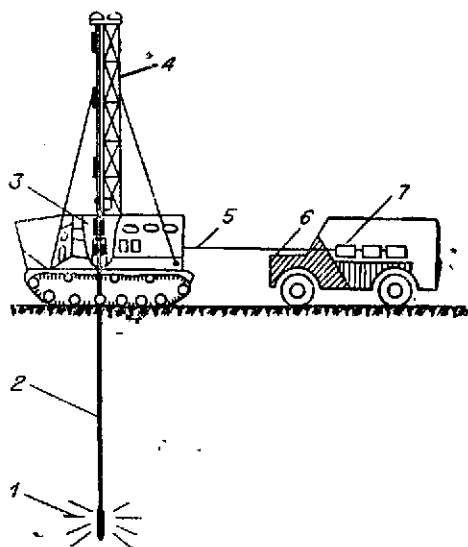


Fig. 4.8. Design of SUGP-10 depth search unit:
 1. depth measuring probe
 2. rod with communication channel
 3. hydraulic device for immersing rods by pressurizing
 4. tower for maintaining rods in working position
 5. communication line to ground recording equipment
 6. equipment station
 7. ground control panel with recording equipment

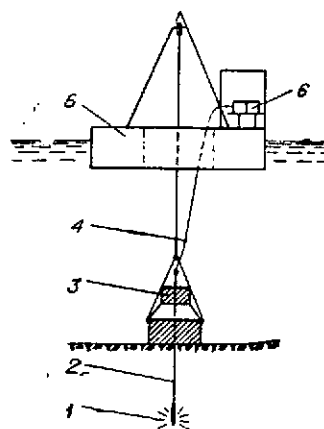


Fig. 4.9. Diagram of underground PSPK penetrating-well-logging station:
 1. measuring probe with source
 2. column of penetrating rods
 3. underwater unit
 4. cable
 5. floating device with rigging
 6. control panel with recording equipment

9. Densimeters for Studying Test Wells

When studying test wells, there is always a gap between the well-logging instrument and the rock. The density of rocks here can be determined using devices pressed against the well wall with springs and surrounded with shields on the side of the well wall farthest from the device. Standard instruments of this type, as shown in Fig. 4.8, began to be equipped with special hoods including lead filters and windows opposite the source and the detector on the side pressed against the well wall. Retaining the instruments with their working side facing the well wall was achieved also by using pressure springs mounted on the housing or the body of the instrument. V. A. Artsybashev built such

a device on the basis of the widely used SRP-2k radiometer. To increase the precision of measurements the radio circuit of the device included a compensatory circuit. The density of rocks can be determined with this device to a relative error of 1-1.5%.

10. Densimeters for Studying Porous Wells

Well walls are not ideally even. This is related to a number of factors. Rocks have different degrees of toughness. Drilling casing during sinking will rub against the rock and damage different rocks to different degrees. In addition, during drilling a well is filled with drilling fluid -- serving to bring particles of the drilled rock to the surface. This liquid is always capable of washing out certain types of rock (especially clayey rock). As a result of these and other factors, vesicles form in wells. Densimeter readings will be affected not only by rock, but also by the drilling solution filling the vesicles. /57

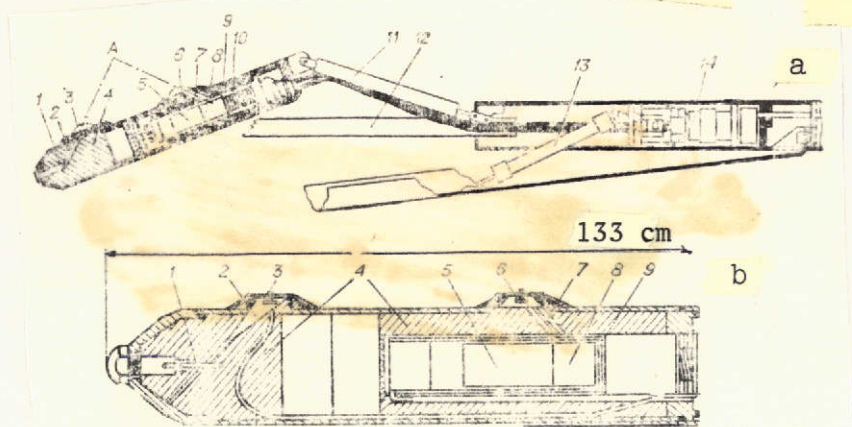


Fig. 4.10. Layout of a single-beam depth instrument (a) and its removable block (b):

1. source
2. collimator
3. source strain gauge
4. tungsten shield
5. photomultiplier
6. detector strain gauge
7. phosphor collimator
8. phosphor
9. Dewar vessel
10. cooling system
11. bracing spring
12. supporting rack
13. hydraulic cylinder
14. hydraulic system control

Geophysicists develop special instruments for investigating these test wells. Thus, J. R. Hearst and R. C. Carlson in the United States developed an instrument based on the single-beam principle for these purposes (Fig. 4.10). With a hydraulic system, a 133 cm long portable device with source and scintillation counter is pressed with its working side against the rock and singly-scattered radiation from the region of point A is recorded (see Fig. 4.10). Strain gage transducers recording the microvesicularity of the rock at these points are placed at the site at which the beam leaves the source collimator and at the site where the beam enters the detector collimator.

The density of rocks can be determined with this device with a relative error not above 2.5%. However, the use of high-activity sources in this device necessitates special measures of radiation safety.

11. Two-Probe Test Well Densimeters

In drilling test wells with clay drilling mud, a clay crust forms on their walls, distorting the results of density well-logging. The thickness of the clay crust is determined by means of vesiculometers. Still, when determining the densities of rocks in these test wells the measurements must be corrected for the effect of the clay crust. In the USSR and abroad, special two-probe densimeters have been developed for test well investigations. The depth instrument in this case houses two scattered gamma-radiation detectors. One detector is placed at a short distance from the source (of the order of 15 cm), and the other -- at a longer distance (of the order of 40 cm). The radiation source and detectors are positioned eccentrically about the body of the device so as to record the scattered radiation from the side of the well wall against which the instrument is pressed. On the side of the far wall of the test well, the radiation source and detector are shielded with lead or tungsten, roughly as in the case of the above-discussed device based on a single-beam principle. The clamping spring here acts as a vesiculometer.

The detector closest to the source takes into account the effect of the clay crust. The result is used in introducing a correction into the readings of the farther-positioned detector. Readings of both detectors can be interpreted either with special nomograms, or else automatically using computers furnished with the equipment.

When the clay crust is not more than 13 mm thick, the density of the rock in oil wells can be determined with these two-probe devices to a relative error of 1-2%.

Similar devices were built also for studying ore test wells. Thus, V. A. Artsybashev showed that using two-probe densimeters, the intermediate zone between the device and rock up to 20 mm in thickness can be cancelled out.

In the United States, devices capable of cancelling out the effect of gamma-radiation from these ores on the results of their density determinations were built for determining the densities of rocks in wells drilled in searching and prospecting for radioactive ores. Using these devices, initially measurements are made of the radiation with the detector in one position within the device. Then, without removing the device from the well, it is again lowered to the face or to the required depth. By means of a small motor housed in the device the size of the probe is changed and the next measurements taken. Natural radioactivity of rock acts identically on the results of the first and second measurements. When one measurement is subtracted from the other, the effect of this radioactivity is cancelled out. The end result depends only on changes in rock density. Operations involved in subtracting measurements are done automatically, with computing devices present in the ground level control panel of the well-logging device.

12. Two-Beam Density Locators

In spite of the availability of a large number of nuclear densimeters employed in investigating test wells, this problem as before disturbs researchers and practitioners. This is so because all existing test well densimeters include in their housing various clamping devices causing a great deal of trouble to fieldmen. Springs can become wedged in a test well, leading to a possible break in the cable or an emergency in the test well. It is not a simple thing to extricate a stuck device from a test well, particularly from oil and gas wells drilled to great depths, to 2-4 km. So one of the vital tasks facing specialists in nuclear geophysics is to develop springless densimeters.

In the Institute of Geology and Geophysics (IGiG), Siberian Division, USSR Academy of Sciences, research is underway on developing one such instrument with a single source and with two detectors housed in cone-shaped annular collimators (Fig. 4.11). Recording singly-scattered radiation makes it possible, from the ratio of the counting rates of both detectors, to acquire information about the density of the rocks from the annular layer around the well bounded in this plane by the triangles ABC and A'B'C'. /59

To measure singly-reflected radiation, extremely high-activity sources must be placed in the device. Therefore, in practice this

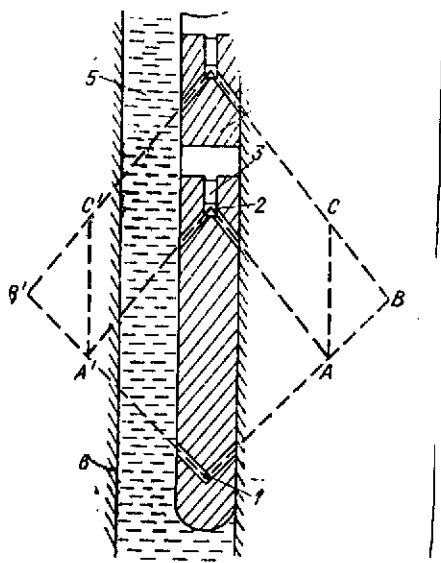


Fig. 4.11. Scheme of two-beam densimeter:

1. gamma ray source placed in collimator
2. gamma-ray detectors placed in collimators
3. photomultipliers
4. lead or tungsten shielding
5. well filling material
6. rock

ABC and A'B'C' = rock sections in which rock density is determined

of 2-3%, and when oil test wells are studied -- to an error of 3-5%.

As the test well is being explored, the device always slides along its wall. This is also due to the fact that the test well virtually always has some inclination from the vertical. So geophysicists have long been dealing with the problem of constructing nonclamping devices that would obtain information only from the side of the device wall in contact with the rock. In the first stage, devices with eccentric shielding housing the radiation source and detector were used for this purpose. In inclined test wells, under the effect of gravity the eccentric shielding always restrains the source and the detector at the rock wall.

method is most simply realized by means of a gamma-ray test well generator. Switching on these generators at a specified depth in the test well is entirely safe for the operator. Coworkers at the All-Union Scientific Research Institute of Nuclear Geophysics and Geochemistry (Moscow) are engaged in developing these devices at the present time.

In the IGiG, Siberian Division, USSR Academy of Sciences, in using gamma-ray sources with the appropriate activity, the approach taken has been to record multiply-scattered radiation. The depth at which this technique can operate is reduced, and instrument readings begin to be strongly affected by the medium filling the test well.

Nonetheless, the studies established that even when recording multiply-scattered radiation, the test well effect can be weakened. Thus, by using 40 mm diameter devices, test wells 50-60 mm in diameter can be investigated, and when using 120 mm diameter devices -- 140-190 mm diameter test wells, and so on. The density of rocks in ore and coal test wells in this case can be determined to an error

Currently, researchers' attention is directed toward building devices with servo systems for acquiring information from the rock on the side of the test well wall along which the device is sliding.

CHAPTER FIVE

RAYS INSTEAD OF FURNACES

1. Beta-Ray Ash Meters

The quality of extracted coal is determined by its content of noncombustible mineral impurities called ash. The content in coal of noncombustible impurities is determined from the weight of the ash remaining after coal samples have been burned in special furnaces. This classical method of determining ash in coals is quite laborious. So recently nuclear methods have begun to be used in testing coal samples for ash. The beta-ray method is most widely used in this function. It is based on irradiating a powdered coal sample with beta-rays and recording with an instrument the rays reflected from the sample. Here it was found that the higher the content of mineral impurities in the coal, the more strongly they will reflect beta-rays. Several devices have been built using the effect of beta-ray reflection. Various detectors are employed in the devices as reflected radiation detectors: ionization chambers, end type gas-discharge counters, and scintillation counters.

Fig. 5.1 presents as an example the layout of a head of a beta-ray ash meter built in the Institute of Geology and Geophysics of the Siberian Division, USSR Academy of Sciences. A general view of the device is shown in Fig. 5.2. With these devices, sample analysis is usually conducted for coals in which the ash impurity constituents do not differ widely in atomic number. Such impurities include alumina Al_2O_3 and silica SiO_2 . Aluminum and silicon present in these oxides differ by one in their atomic number. The ash content of these coals can be determined by this 61 technique in 2-3 min with an absolute error of 0.2-0.3%.

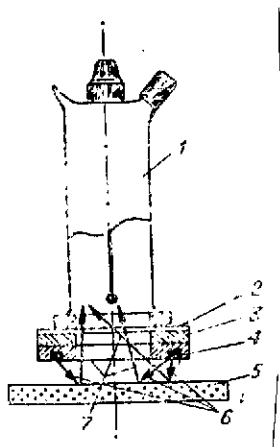


Fig. 5.1. Schematic diagram of head of beta-ray ash meter

1. end type beta-counter
2. aluminum filter
3. lead insert not admitting bremsstrahlung radiation from source to working region of detector
4. beta-radiation preparation
5. sample
6. primary radiation exiting from source
7. reflected radiation directed toward window of end type counter

The situation is more complex when analyzing coals whose ash impurities are more diverse. Thus, some coals contain compounds of iron, calcium, and sulfur, whose atomic numbers differ widely from aluminum and silicon. In the USSR, to analyze these coals, A. A. Golev developed a technique with two ionization chambers operating on the compensatory principle. Under this method, the test sample is divided into two parts. Each sample portion is irradiated with a separate source. One chamber records the total flux of reflected radiation while the other records only the flux associated with the ash impurity. The radiation scattered from the carbon in the sample is suppressed with a thin aluminum filter interposed along the path of the recorded flux of reflected beta-rays. The difference current from these chambers is independent of the change in the atomic number of the ash impurities in the range from 11 (sodium) to 26 (iron), but depends only on their amount, which determines the coal ash content.

The beta-ray analyzers discussed here can be used not only in analyzing coal, but also ore samples. About ten chemical elements can be analyzed with these devices, with a sensitivity threshold from 0.1 to 1%.

The measurements are taken according to the procedure of single reflection of beta-radiation from the test samples.

However, if the test sample consists of two parts and the beta-radiation source is situated between them, the beta-rays can be successively scattered from the upper and lower layers, that is, they can be multiply-reflected. When this reflected beta-radiation is recorded, as shown by L. M. Boyarshinov and M. M. Sinyavin, the sensitivity threshold can be reduced by one order.

2. Gamma-Ray Ash Meters

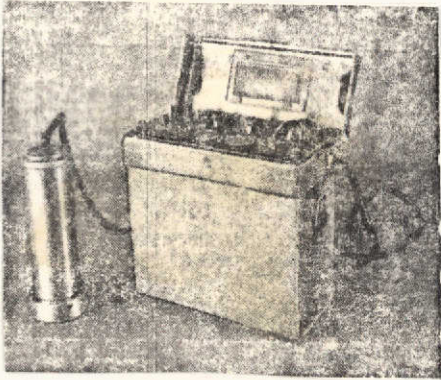


Fig. 5.2. External view of beta-ray analyzer

Soft gamma-radiation in the approximate range 15-80 kev is intensely by the atoms of a material owing to the photoelectric effect. The higher the atomic number of the element Z , the more intensely soft radiation is absorbed. The coefficient of the photoelectric absorption of gamma-radiation rises in proportion to Z^4 , therefore the more impurities with high atomic number present in the coal, the more strongly the coal will weaken the flux of gamma-radiation striking it. This effect is also used by geophysicists when determining the ash content of coals. If the fraction of reflected beta-radiation rises with increase in the atomic number of the ash impurities, the fraction of the reflected gamma-radiation falls off. /62

The presence in ash impurities of compounds of iron and calcium also distorts the results of determining coal ash by this technique. The problem of eliminating the effect of changes in these elements occurring during sample analysis has not yet been entirely solved. Therefore, gamma-ray ash meters have not found wide use compared with beta-ray ash meters.

However, gamma-ray ash meters based on transilluminating a coal mass traveling along a conveyor belt are used in practice. Since the flow of coal on the conveyor is in an uneven layer, it is irradiated with two sources. Using one source, the mass of the coal traveling along the belt is evaluated and a correction is determined, which is then inserted into the measurements based on the second source. These devices are used not just in determining coal ash, but also for automatically rejecting country rock from the coal flow.

3. Determining Coal Ash at Coal Bedding Sites

The laboratory methods of nuclear analysis of the ash of powdered samples considered above, even though quite rapid compared with the technique based on sample combustion, are not free of disadvantages. The coal samples must be selected, brought to the laboratory, ground and rubbed into powder, and only thereupon can the operator begin analyzing the samples.

However, when it is necessary to estimate the ash content directly during the exploitation of a bed, the above-examined beta-ray analyzer is resorted to for assistance (see Fig. 5.2). Since the irregularities in the irradiated surface distort the results of determining coal ash, an even area about the size of a heel is produced at the measurement point in 2-3 min with an ordinary drill equipped with a special milling cutter. This same amount of time is sufficient for a measurement. For coals with light ash impurities, their content is determined using this ash meter with an average absolute precision of 0.4%. Testing of the device showed that its introduction will mean a large economic benefit.

4. Study of Coal-Prospecting Wells

/63

In the prospecting of a coal deposit, wells are drilled, thus revealing the number of coal strata, and their thickness and ash content. These strata are necessary to calculate the reserves of deposits and to determine coal quality. In the first stage of studying test wells, the coal strata are discovered from the drilling data. Coals, in contrast to their intervening rocks (sandstones, clay shale, and so on), have reduced toughness with respect to the rate at which a drill can be driven through them. Still, this is a very difficult method of finding coal beds. The thickness of coal strata here is determined highly approximately, and some coal strata are bypassed altogether. When sinking wells, the drillers have the job of choosing the core (cylindrical rock samples). The core samples of rocks thus obtained are sent to the laboratory for their physical properties and ash content to be determined.

The technique of finding coal strata by the profiles of test wells and the determination of their ash content is quite laborious, so geophysicists began using various test well methods (electrical and others). However, these methods proved to be low in effectiveness, and again geophysicists turned to rays for assistance. Since beta-particles do not deeply penetrate matter, a more penetrating radiation is needed to penetrate test wells -- gamma-quanta. This radiation is capable of being scattered by the electrons of a material. By recording scattered gamma-rays, the specific density of coals can be determined, and from their photoelectric absorption one can evaluate their quality.

Coals differ in density by about a factor of 1.5-2 from their intervening rocks. As a result, higher intensities of scattered gamma-radiation are obtained on plots of coal strata. With the technique of scattered gamma-radiation, coal strata are quite sharply fixed from the profile of test wells and their thickness is determined. We examined the layout of nuclear densimeters in Chapter Four.

Special devices based on recording soft scattered gamma-radiation in the approximate range 30-100 kev have been built to determine the ash content of coals in test wells. Since instrument readings are strongly affected by deviations of the instrument from the test well walls, their roughnesses, and their filling with drilling mud, the probe of the instrument has begun to be placed in removable blocks, that is, roughly as is the case with a certain type of densimeter (see Fig. 4.10). With these devices constructed on the basis of gas-discharge counters and thulium gamma-preparations ($T = 129$ days, $E_\gamma = 52$ and 84 kev), the ash content of coals can be determined with an absolute average error of 2%. When working with a spectrometer, the measurement error can be lowered to 1%. /64

Since devices with clamping units are inconvenient to use, lately neutron well-logging devices have begun to be developed. Coal contains, along with carbon, large amounts of hydrogen. This then favors the use of neutron techniques for discovering coal beds. This possibility is associated with the fact that when colliding with hydrogen nuclei (protons), neutrons lose a large fraction of their energy and are effectively slowed down. Carbon is also a good moderator. Therefore, coals (especially lignite) are clearly ascertained in neutron well-logging diagrams. The roughnesses in the well walls here distort much less the readings of the neutron techniques compared with the gamma-ray techniques. When atomic nuclei capture neutrons, hard gamma-radiation is produced. By recording this radiation with spectrometers, it proved possible to determine the ash in coals with an absolute error of 3%.

Nuclei of aluminum atoms and silicon atoms present in the ash impurities of coals are easily activated with neutrons. This makes it possible also to judge the ash content of coals from the change in their induced activity. It turns out that the ash content of coals in the 10 to 50% range can be determined with an absolute error of 1-5%.

CHAPTER SIX

SCATTERING AND ABSORPTION

1. Scattering with Absorption

Chapter Four discussed the use of Compton scattering of gamma-rays in nuclear prospecting for the determination of rock density. In particular, it was pointed out that when making measurements of scattered radiation with large probes, the intensity of the radiation recorded falls off with rise in rock density not only owing to the more intense scattering of gamma-rays, but also due to their absorption via the photo-effect. In fact, any successive scattering of gamma-rays in general ends ultimately in their photoelectric absorption, that is, scattering always borders on absorption.

The presence in rocks of heavy chemical elements (lead and ⁶⁵others) leads to the even more intense manifestation of the photoelectric absorption of gamma-rays. This, in turn, results in a reduced intensity of the gamma-radiation recorded. Thus, the heavier the elements in rock, the lower the intensity of the scattered radiation recorded by the device. From the decline in the intensity of scattered radiation one records the content in ores of heavy chemical elements. The preceding chapter already recounted the use of a combination of these two effects in determining coal ash content. Let us look at these effects as utilized to determine the content in ores of various metallic minerals (iron, antimony, tungsten, lead, and so on).

A method based on these two phenomena of gamma-ray interaction with matter is called the selective gamma-gamma method (GGM-s) in nuclear geophysical literature. Intensimetric and spectrometric techniques of measuring scattered radiation are employed to find the content of heavy elements in rocks. The intensimetric method in this case is based on measuring the total

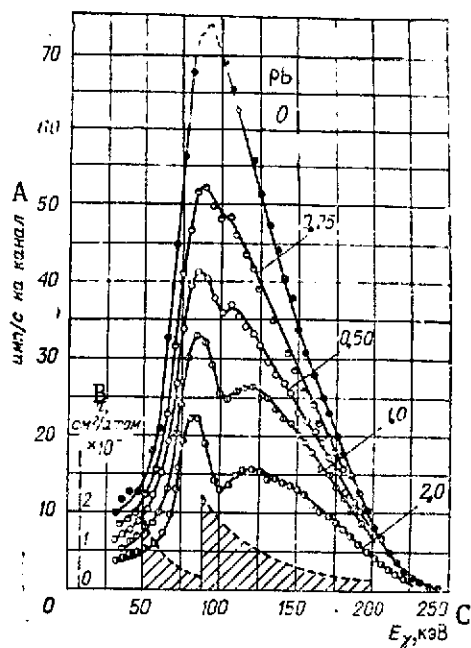


Fig. 6.1. Spectrum of scattered gamma-radiation measured in test well (after M. M. Sokolov et al.) Numbers alongside curves represent concentration of lead in sand in weight percent (dashed curve shows change in coefficient of photoelectric absorption of gamma-radiation in lead)

KEY: A. pulses/sec per channel
B. cm^2/atom
C. keV

(overall, or -- as sometimes used -- the integrated) flux of scattered radiation. In spectrometric measurements, scattered radiation is recorded in several fixed energy ranges, that is, by parts (differentially); therefore often the spectrometric method of measuring gamma-radiation in specific ranges is called the differential method. The spectrum of scattered gamma-radiation recorded when measurements are taken of models -- in sand with different lead content -- can be judged from the data in Fig. 6.1. As we can see, a rise in the lead content in sand leads to a decrease in the area under the curve. The dip in the area of approximately 100 keV is associated with the absorption of gamma-radiation owing to the K-quantum jump of lead. Measurement of the differential spectrum of gamma-rays in the region of this dip affords a reliable evaluation of the lead content in the ore.

/66

2. Analysis of Core Samples and Crushed Samples

A long series of devices have been built in the USSR for determining heavy elements in ores. Cores and crushed samples can be analyzed with the technique under discussion.

In the core meter, radiation from the source strikes the core sample, is scattered in it, and through a window in the lead shielding reaches the detector. The lead shielding simultaneously with filters placed on the path of the primary gamma radiation can soften the radiation, that is, serve as a kind of moderator of the high-energy gamma-rays.

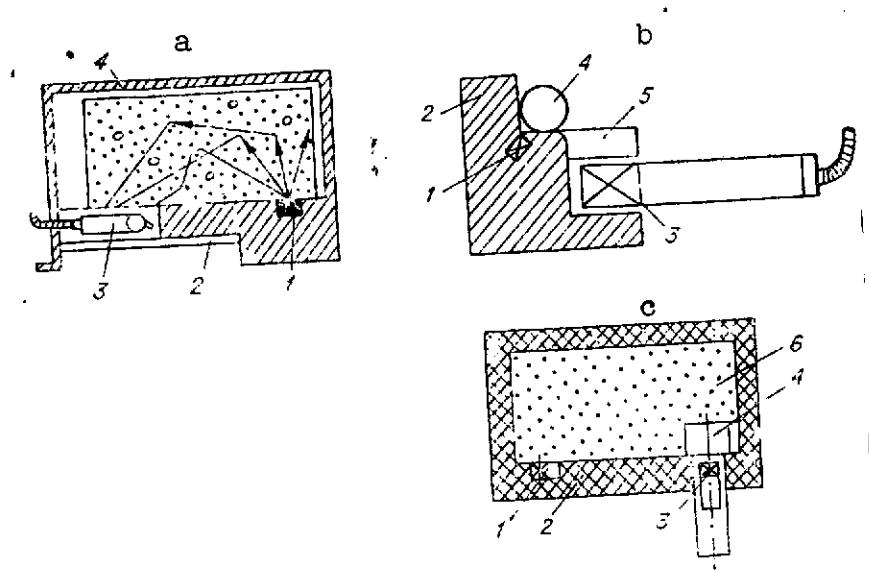


Fig. 6.2. Schematic diagram of devices for analysis of large-volume samples (a -- after V. N. Balashov et al.), for analysis of cores (b -- after A. P. Zarubin et al.), and for analysis of small-volume samples (c -- after V. N. Smirnov et al.):

1. gamma-radiation source
2. lead shield and housing
3. detector
4. test material
5. entrance window
6. sand moderator

A crushed sample can be analyzed in vessels of large (Fig. 6.2 a) and small volumes (Fig. 6.2 c).

When working with the devices (Fig. 6.2 a and b), one fixes the measurements by the intensimetric technique. In this case one can evaluate only the overall content of lead in the test materials. The presence in **crushed** ore of 70% zinc is equivalent to its content of 1% lead.

In the device with small weighed samples (Fig. 6.2 c), the hard radiation is softened in the sand. Here the sand is irradiated only with a flux of scattered radiation. The use of the spectrometric technique of measuring radiation passing through the sample permits separate determination of the sample content of lead and barium.

3. The Study of Walls of Mine Workings and Test Wells

Devices based on measurements taken by the intensimetric and spectrometric technique are used in solving these problems. In conducting the investigations, it was established that the instrument readings are significantly distorted owing to the effect of irregularities in the irradiated surfaces and changes in the density. To eliminate these factors, special measurement procedures began to be used, which will be examined below when we discuss each of the techniques under consideration.

Devices of models RSR-2 and RSR-3 with scintillation counters were built for measurement by the intensimetric technique (Fig. 6.3). The air gap between the irradiated flat surface of the rock in the transducers in Fig. 6.3 a and b is taken as the optimal /68 in order to attain the maximum intensity of reflected radiation and to eliminate the irregularities in the irradiated surfaces. The use of a ring-shaped source of low-energy radiation (50-80 kev) in these devices (Fig. 6.3 a) makes it possible to avoid the effect of changes in rock density on the results of determining heavy element content in the rock. In the instrument shown in Fig. 6.3 b and c, this effect is achieved by using two sources placed at different distances from the detector. With the appropriate ratio of the selected source activities, not only the effect of changes in the densities of the rocks under study eliminated, but also the effect of irregular surfaces.

Using these devices, when exploring the walls of workings and test wells, one can determine the content of iron in ores with a sensitivity threshold from 2 to 5%, the content of antimony and tin with a sensitivity threshold from 0.2 to 0.6%, and the content of tungsten, mercury, and lead with a sensitivity threshold from 0.1 to 0.3%. And these scatter ranges are mainly associated with changes in the material composition of the ores.

When gamma radiation source is used in the spectrometric devices. The effect of irregularities in the surfaces irradiated and changes in rock densities on measurement results here is eliminated when the ratio of counting rates in the two channels is recorded (see Fig. 6.1). Thus, when determining lead in ore, the spectrum of scattered radiation is measured in the approximate range 95-105 kev (the region of the spectral dip) and 150-160 kev.

When several heavy elements are present in ore at the same time, the scattered radiation spectrum must be measured in a larger number of channels. With this spectrometric technique of measurements, the content of iron ores can be determined beginning at 2-3%, and the content of lead -- starting at 0.2-0.5%, when barium is present in ores.

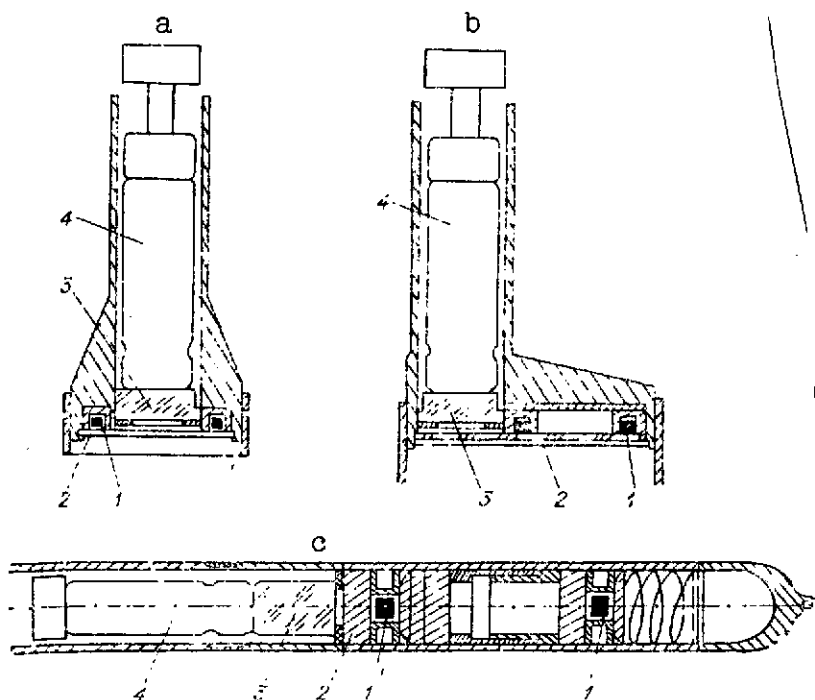


Fig. 6.3. Schematic diagram of transducers in an RSR-2 device for measurements of samples and exploration of mine workings by the technique of radiation reflection (a), for exploration of walls of mine workings with changes, using two sources (b), and for exploration of walls of dry test wells when taking measurements with two sources (c):
 1. sources 2. lead shielding 3. phosphors
 4. photomultipliers

Use of these techniques in searching and prospecting for minerals will mean an annual saving per deposit in the range 100,000-300,000 rubles.

CHAPTER SEVEN

EACH HAS ITS OWN CHARACTER

1. How Can Atoms Be Compelled to Display Their Character?

Under the effect of radioactive radiation, electrons can be ejected from the orbits of atoms of chemical elements. Here the atoms are in an excited state. If, for example, an electron is ejected from the K-shell nearest the nucleus, an electron from the L-shell strives to fill its place, and so on. When an electron from the L-shell passes into the K-shell, a photon with a highly characteristic energy is emitted from the atom. In atomic physics this is the characteristic energy. The energy of the characteristic radiation varies in relation to the atomic number of the chemical elements. The larger the atomic number of the chemical element, the greater the energy with which the excited atom can emit photons. By recording this radiation, one can judge the content in the medium under study of chemical elements. In other words, from the displayed character of each element one can judge how much it is contained in the rocks and ores under determination.

/69

In the literature, this method of studying rock and ore composition is called the rock X-ray-radiometric method. This is associated with the fact that the characteristic radiation is X-ray and it is measured with radiometric equipment.

In the practice of X-ray-radiometric analysis, alpha-particles, electrons (beta-rays), and gamma-quanta can be used as sources of exciting radiation. However, usually the characteristic radiation of targets made of various chemical elements is used as the exciting radiation. Under the action of the primary radiation, the characteristic radiation is produced in these targets, which is then used in irradiating the media under study. By varying the target material, one can obtain characteristic radiation with different energy and thus excite different elements in the media being tested.

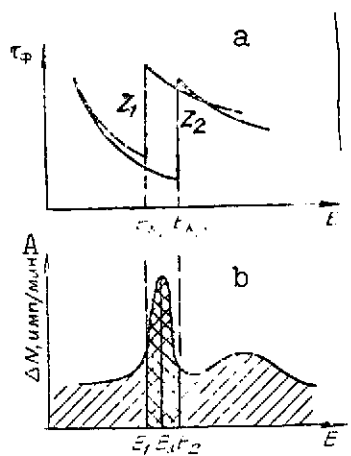


Fig. 7.1. Illustration for the explanation of principle of differential filters:

- a. dependence of linear coefficients on energy of gamma-radiation for elements with atomic numbers Z_1 and Z_2 ($Z_1 + 1 = Z_2$)
- b. spectrum of characteristic radiation of element being determined, measured by the difference in the readings

KEY: A. pulses/min

Intensimetric and spectrometric detectors are used in recording characteristic radiation. Spectrometric detectors find the greatest scope of use.

The characteristic radiation involving the use of intensimetric counters can be discriminated by using differential filters. About it was shown (see Fig. 6.1), that in the region of low energies from fractions of a kev to approximately 150 kev, absorption jumps are observed in the graphs of the coefficients of photoelectric attenuation of the radiation. Thus, for lead the jump occurs at the energy of 87.6 kev. For other elements it will take on different values. L-jumps are evident besides the K-jumps.

So if in the path of the flux of ⁷⁰ the radiation being recorded alternately a filter with K- or with L-jump is placed in front of the detector (above and below the energy of the characteristic radiation of the element being determined), we will correspondingly initially suppress the interfering radiation to the right of the peak of the radiation being recorded, and the second time we will record mainly radiation to the left of this peak. The difference reading here will correspond to the filter transmission band (Fig. 7.1).

Proportional and scintillation counters are used as spectrometric radiation detectors, as well as semiconductor counters.

In geophysical investigations, the X-ray-radiometric method initially was used only in laboratory analysis of material, while at the present time it has gone beyond the laboratory.

2. Analysis of Samples in the Laboratory

A long series of devices have been built for analyzing samples in the laboratory. A scheme of one is shown in Fig. 7.2.

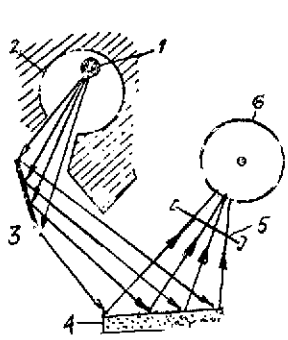


Fig. 7.2. Scheme of mutual arrangement of elements of X-ray radiometric device:

1. source of primary radiation
2. shielding
3. intermediate target
4. sample
5. differential filter
6. proportional counter

Primary radiation via an opening in the shielding strikes the intermediate target and excites characteristic radiation in it. This radiation in turn acts on the sample and excites in it the characteristic radiation of the elements being determined, which is recorded with some detector. Differential filters placed on the path of the flux of the radiation being recorded can be used to suppress the interfering radiation.

In some devices, the samples are irradiated directly by the primary radiation of the source.

Devices with scintillation counters are used for determining chemical elements with atomic numbers from 25 (copper) and higher in samples, and with sensitivity threshold from 0.01 to 0.05%. Devices with proportional counters can be used for determining chemical elements with atomic numbers

from 13 (aluminum) and higher and with sensitivity threshold in thousands of a percent. Using devices incorporating semiconductor detectors, the content of several elements in samples can be determined to ten-thousandths of a percent.

Recently, in place of radioisotope sources, in sample analysis electronic and X-ray tubes have begun to be used. By suppres- /71
sing different voltages in these tubes, one can vary the energy of the radiation acted on the material under study or at an intermediate target and selectively acted on the element under analysis. Thus, when samples are irradiated with electrons from an electron tube, elements with atomic numbers 5 (boron) and higher in samples can be analyzed.

In analysis, not only is a method based on measuring the radiation leaving the irradiated surface of the sample used, but also a method of analysis based on transillumination of the samples with characteristic radiation.

3. Study of the Composition of Earth and Lunar Rocks in Their Natural Bedding

In the All-Union Scientific Research Institute of Prospecting Geophysics (VIRG), techniques and equipment have been

developed for testing the walls of mine workings. Here the transducer is similar to the one shown in Fig. 6.3 A. This transducer is intended for recording softer radiation compared with the radiation used in the technique described in Chapter Six. Accordingly, thinner scintillators (about 1 mm) must be used in X-ray-radiometric transducers. In addition to devices with scintillation counters, devices with proportional counters can also be used for these purposes.

The technique of spectral ratios in this case as well makes it possible to bypass the effect of irregularities in the irradiated surface and changes in rock densities. The sensitivity threshold of elements with atomic numbers from 20 (calcium) and higher is estimated at 0.1-0.3%. When semiconductor detectors are used, the sensitivity threshold can be lowered to 0.01-0.03%.

A device based on proportional flow counters was developed in the VIRG for the determination in rocks of elements as a vehicle is in motion. The transducer together with source and counter are mounted on the rear axle of a GAZ-69 truck 7-8 cm from the ground level, and the instrument panel is in the body of the truck. Investigators have shown that the absence of soil cover, this method can be used to determine the content of iron, titanium, and zirconium in several types of rock. When these elements are being determined, the truck can travel along the prospecting routes at speeds up to 20 km/hr.

V. A. Meyer et al. (Leningrad University) proposed and implemented a test well logging method of determining a long series of chemical elements in ores.

Clamping devices with one or two radiation sources as well as centered devices are used for investigating test wells at the present time (Fig. 7.3). The use of two radiation sources, as in the equipment of selective gamma-gamma-well-logging (see Fig. 6.3) eliminates the effect of irregularities in the walls of the test well on instrument readings. Instruments of the centered type provide information from the entire test well perimeter. In addition to these types of instruments, still others are in use.

In order for primary radiation and the recorded characteristic radiation to be negligibly weakened, an entrance window made of materials with low atomic numbers (textolite, beryllium, and so on) is built into the body of the instrument opposite the collimators.

Using six-channel analyzers employed in devices for X-ray-radiometric well-logging, three constituents in the ores can be

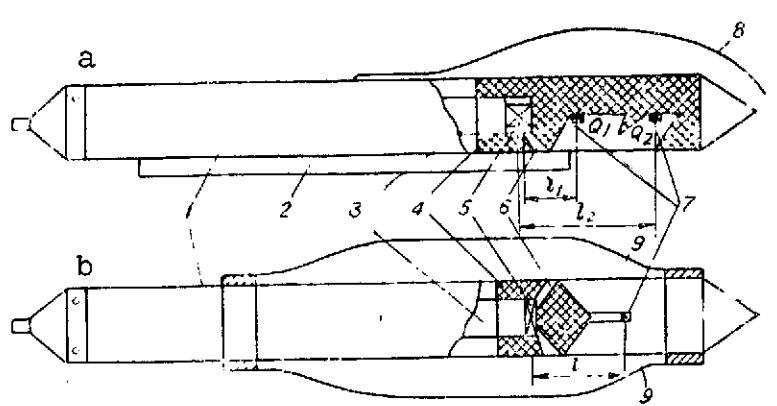


Fig. 7.3. Layout of X-ray-radiometric well-logging devices of the clamping type with runners /slides/ (a) and of the centered type (b), after Yu. A. Grinshteyn:

1. body of device
2. runners
3. photomultiplier
4. lead shielding
5. phosphor
6. collimation aperture
7. radiation source
8. clamping spring
9. centering springs

determined at the same time. Thus, in polymetallic ores, lead, barium, zinc, and iron can be determined simultaneously. In addition, with this technique the content of tin, antimony, molybdenum, tungsten, and uranium can be determined in test wells. The sensitivity threshold for all these elements is estimated at 0.1-0.3%.

A special RIFMA device based on this technique was installed in the self-driven Lunokhod-1 laboratory landed on the lunar surface on 17 November 1974 integrated studies. This, in particular, is also reflected in its name, which is amplified as follows: X-ray isotopic fluorescent method of analysis. Lunokhod was engaged in performing its designed functions for 10.5 months with regular interruptions associated with the phases of the Moon. (Since Lunokhod replenished its energy reserves with solar batteries, /73 as soon as Lunokhod enters the shadow cast by the earth, it is placed on "rest").

A scheme of a portable instrument transducer in the course of measurements is shown in Fig. 7.4. The device is equipped with two titanium-tritrium sources. The characteristic energy of the

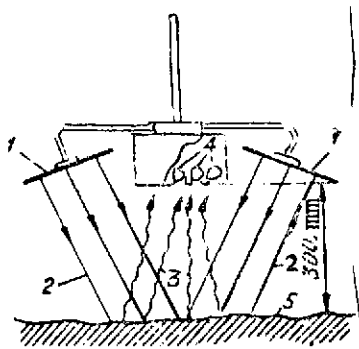


Fig. 7.4. Scheme of measurements using RIFMA device:

1. sources
2. direction of flux of primary radiation
3. secondary characteristic radiation directed toward detector
4. proportional counters
5. irradiated rock

rock-forming elements is measured with a system of proportional counters and differential filters. The spectrum is analyzed with a 64-channel analyzer.

The instrument is designed to determine rock-forming elements when it is stopped and when it is in motion. The results are in complete agreement with the data of an analysis of lunar rocks made by Surveyor craft, and also with the data of the analysis of rock samples brought back by Apollo crews and by the Luna-16 automatic station¹. Lunokhod-2 landed on the surface of the Moon on 16 January 1973 was also equipped with a RIFMA device. Its radiation source was a zirconium-tritium preparation making it possible to determine **rock**-forming elements all the way up to calcium, titanium, and iron. This Lunokhod has also /sic/ functioned about 4.5 months. In the transition from "maria" rock to "highland" rock, a decrease in iron from 10-12 to 4% was recorded.

4. X-ray Equipment in Geology

More powerful fluxes of exciting radiation compared to fluxes obtaining from radioisotope sources can be produced with X-ray tubes.

We know that the possibility of using X-ray radiation for the analysis of material was established in 1913. Since then, X-ray spectral analysis has begun to be used in studying material, in particular, geological samples. There are two main modifications of X-ray spectral analysis: a modification based on electron irradiation of a material deposited on the tube anode (the method of primary excitation), and a modification based on irradiating the test material with X-ray radiation from the tube anode (method of secondary excitation). In both cases, the characteristic radiation is measured with special crystal-analyzers and the radiation is recorded on photographic film. /74

¹ All these data are in Chapter Thirteen.

In the nuclear-physical (atomic-physical) variant, the X-ray spectral methods have begun to be realized since the moment scintillation counters of nuclear radiation have been introduced into science and technology (see Section 2, Chapter Two). These counters began to be used in analyzing the spectrum of characteristic radiation. Recently, proportional and semiconductor counters have been in use for this purpose.

The first X-ray equipment weighed about 100 kg. They were employed exclusively in laboratory conditions. Lately, portable X-ray devices weighing about 10 kg have begun to be constructed. At the present time the Soviet investigators N. V. Belkin, E. A. Avilov, et al. have developed devices weighing about 1 kg.

Portable devices for analyzing geological materials and field conditions can be built on the basis of miniature **sources** of X-ray radiation. This kind of device naturally can be housed in space laboratories of the Lunokhod-1 type, and others.

British investigators have already built a device for irradiating samples with electron fluxes. With it, chemical elements beginning at boron can be analyzed (see Fig. 1.1).

CHAPTER EIGHT

"ENCOUNTER" OF RUDOLF MOSSBAUER WITH CHRISTIAN DOPPLER

1. How Did This "Encounter" Happen?

The name of the German physicist Rudolf Mossbauer began to be known after his 1957 discovery of the resonant absorption of gamma-rays, which came to be called the Mossbauer effect. The Austrian physicist Christian Doppler (1803-1853) discovered a phenomenon, which essentially amounts to a change in the frequency of sound vibrations received from a source travelling relative to the observer, and vice versa. It is inherent, as was **subsequently** shown, to all **wave** processes. In honor of his discovery, this phenomenon was called the Doppler effect (1842). Can there be something in common between these two phenomena discovered more than 100 years apart?

Gamma radiation also is wavelike in nature. The relation between energy E and frequency ν of this radiation is given by the expression

$$E = h\nu, \quad (8.1)$$

where h is Planck's constant.

Thus, a frequency change can be observed also for gamma rays. 75 Therefore it proved possible by combining the Mossbauer effect with the Doppler effect to develop equipment for detecting several chemical elements in material.

Let us examine the Mossbauer effect more closely. Essentially it amounts to resonant fluorescence of gamma rays when they are emitted, absorbed, and scattered without losing energy in the recoil of the emitting and absorbing nuclei of the elements. Resonant fluorescence is observed when a nucleus passes from the excited state to the ground state, with the emission of a photon with

specific frequency. When this photon passes through a medium (target) consisting of the same element as the emitter, it can be absorbed. As a result, the target nucleus can pass into the excited state and, in a short time, return to the ground state, emitting a photon with the same frequency. Here weakening of radiation in the direction of the primary photons and emission from the target of new photon with the same frequency in all directions are observed. Strictly speaking, this then is what resonant absorption and scattering of photons by the nuclei of the irradiated medium amount to. Nuclei of emitting or absorbing atoms must be bounded in a crystal lattice at a temperature not more than 290° (Kelvin). In this case in view of the large mass of the emitting (absorbing) system, the photons are de-excited without the expenditure of energy in recoil. In other words, the handle of the weapon must be sufficiently massive so that when a projectile is fired no recoil is experienced.

Resonant absorption of gamma radiation passing through a sample or scattered by it **becomes** evident with the highest sensitivity when there is the slightest deviation of the gamma rays from their resonant frequency (energy). A change in the gamma-ray frequency is attained in different ways, in particular, vibration of the absorber relative to the source (or vice versa). In this case owing to the Doppler effect, the absorber will receive gamma radiation at an altered frequency. By moving the absorber relative to the source at different rates and by measuring the corresponding intensity of the radiation passing through the absorber or scattered (reflected) by it, we can obtain the Mossbauer absorption curve (spectrum). This combination of two effects can reveal several chemical elements and their compounds in media studied with high sensitivity.

Resonant absorption of gamma quanta in the general case depends both on the structure of the source and absorber nuclei, and on the ambient conditions (temperature, electromagnetic and gravity fields, nature of chemical bonds, and so on). This can account for the broad fields of the use of the Mossbauer effect in physics, chemistry, technology, geophysics, and so on.

The Mossbauer effect becomes evident for the vast majority of elements with large width of excitation level at low temperatures near absolute zero, in the absence of electrical and magnetic interference. All this means certain difficulties in applying this technique. The effect is observed most simply for tin and iron.

Scintillation counters are ordinarily used in recording radiation when implementing the Mossbauer effect. In addition, for some elements to be detected with this effect, special resonant counters are used based on gas-discharge counters. Their difference from ordinary gas discharge counters lies in the

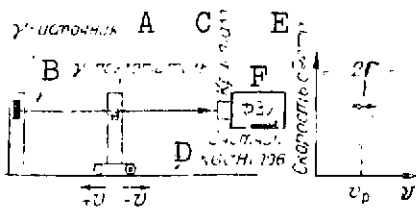


Fig. 8.1. Schematic diagram of device for measuring Mossbauer absorption spectrum of radiation passing through same (Γ = half-width of absorption curve)

KEY: A. γ -source
B. γ -absorber
C. Crystal
D. γ -quanta counter
E. Counting rate

cathode, which is made of materials containing the isotope of the element being determined. The manifestation of the Mossbauer effect for the nuclei of the cathode atoms leads to the formation of electrons of internal conversion; by recording these, the element sought for in the samples is determined.

2. Use of Resonant Absorption of Gamma-Quanta

A schematic diagram of a device of measuring the Mossbauer spectrum of resonant absorption of gamma quanta is shown in Fig. 8.1. By recording gamma rays passing through

an absorber travelling at variable velocities relative to the source, one can obtain the dependence of the recorded counting rate on the absorber travel rate. This dependence is also schematically shown in Fig. 8.1. The change in the frequency of gamma radiation in such devices can be achieved by using various membranes, rotating disks with sources, piezo-transducers, as well as magnetic and gravity fields.

The samples are measured at a zero velocity N_0 and at some maximum velocity (3 mm/sec) N_v . Resonant absorption can become evident in setting up the function

$$M = \frac{N_v - N_0}{N_v} = 1 - N_0/N_v : f(p), \quad (8.2)$$

where p is the concentration of the element under study in the sample.

The operation involved in arriving at the function (8.2) can be automated by simultaneous irradiation of two identical samples, which one is at rest, and the other is in motion (Fig. 8.2). At zero concentrations of the elements being determined in both samples, we will get a zero signal at the output. An increase in the content of the element determined in the sample leads to a rise in the difference signal.

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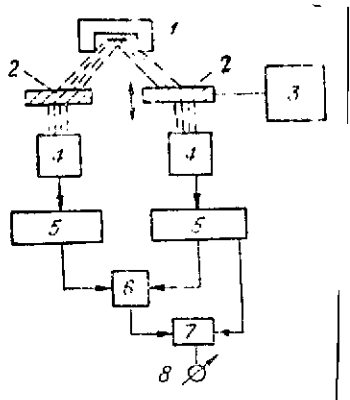


Fig. 8.2. Block diagram for measurements of resonance absorption based on the gamma-method

A technique is being developed on the basis of this principle, and a device is being built for analyzing samples for tin. Since the ore-extracting industry is mainly interested in tin dioxide SnO_2 (cassiterite), Mossbauer devices are built for determining precisely this tin compound in samples. Other compounds present in ores shown in practically no interference with the determination of cassiterite. This is one of the key advantages of methods based on the Mossbauer effect.

In these devices, SnO_2 preparations with the radioactive isotope **tin-119 m** ($T = 270$ days, $E_\gamma = 23.8$ kev) are used as the gamma radiation forces. An isotope with this mass is encountered in natural compounds of tin in the amount of 8.6%. The content of cassiterite in ore based on previously constructed calibration graphs is then determined by the manifestation of the Mossbauer effect for this **isotope**.

In the USSR, a special tin finder MAK-1 (Mossbauer analyzer of cassiterite, shown in Fig. 8.3) has been built for determining tin in ores. The control panel of this device can be operated alternately with heads based on absorbing and scattering gamma rays from the media under study. The next section will discuss the layout of the head based on the scattering effect. /78

The sensitivity threshold of the MAK-1 device with a head based on gamma-ray absorption is estimated as 0.05%. Using devices with resonant counters, the threshold of sensitivity for tin can be lowered to 0.01%. By measuring samples with the Mossbauer device and with an X-ray-radiometric analyzer, one can determine tin bound in cassiterite, and total tin.

The technique of resonant absorption of gamma rays is used also for determining iron compounds in samples. Thus, in the US these instruments were used for determining compounds of iron in samples of lunar rock brought back to earth by the crews of Apollo 11 and Apollo 12.

3. Use of the Phenomenon of Resonant-Scattered Gamma Rays

A schematic diagram of the head of a transducer based on this effect is shown in Fig. 8.4. The optimal angles are $\alpha = 0$ and $\beta = 60^\circ$.

A photograph of the head of the MAK-1 Mossbauer device based on gamma-ray scattering is shown in Fig. 8.3. Using this device, the **cassiterite** content is determined in the surface appearance of bedrock: outcroppings and the walls of mine workings. The sensitivity threshold of the device for tin is estimated at 0.1%. Introducing this instrument in the practice will mean a savings of 14,000 rubles per year per device.

Devices for determining cassiterite in the walls of dry test wells have also been built on this principle.

By integrating the measurements of Mossbauer devices with X-ray-radiometric equipment, one can determine the content in ores of cassiterite and total tin.

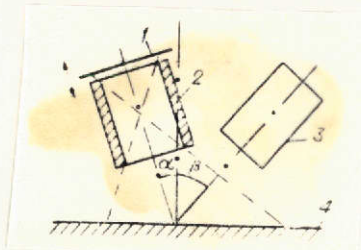


Fig. 8.4. Scheme of measurements based on the gamma-method of resonant scattering of gamma-rays:

1. gamma-radiation source
2. lead collimator
3. detector
4. irradiated rock

NUCLEAR BILLIARDS

1. Effect of Neutrons Colliding With Protons

Neutrons and protons are of approximately the same mass. Elastic collisions of neutrons with protons obey the ordinary laws of mechanics; a classic example of these is the collision of billiard balls. On impacting, a neutron transmits part of its energy to the proton. In a head-on impact, the neutron can transmit all of its energy to a proton.

In similar interactions of neutrons with the nuclei of atoms of other chemical elements, in collisions the neutron will transmit on the average much less energy compared with the energy transmitted to the proton. Here the larger the mass of the nucleus, then on the average the smaller the energy the neutron will transmit to this nucleus.

Thus, protons are highly effective moderators of fast neutrons emitted by sources. Therefore hydrogen-containing media are used as elements of shielding materials protecting against neutrons. This property of hydrogen is used by geophysicists also in determining the moisture of rocks and soils.

Neutron devices for determining the moisture of samples in the laboratory and directly in bedrock outcroppings and in soils have been built based on this principle of neutrons interacting with protons.

2. Laboratory Moisture Meters

The layout of one device built in the Institute of Geology and Geophysics, Siberian Division, USSR Academy of Sciences, which can be used in determining rock moisture, is shown in Fig. 9.1. The device consists of two moderating blocks about 25 cm in diameter.

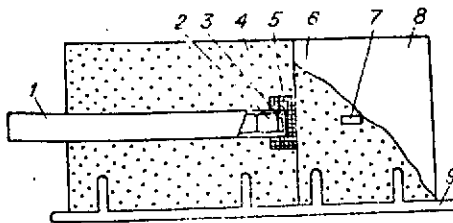


Fig. 9.1. General view of scintillation device (SNU) based on SRP-2 field radiometer:

1. radiometer case
2. photomultiplier
3. neutron phosphor
4. body of device
5. cassette and sample
6. moderator (water or paraffin)
7. neutron source
8. cadmium
9. support

The source block here has a length of 15 cm, and the detector block -- 25 cm. To replace cassettes containing samples, the source block can be rotated about the axis of the rod relative to the detector block. The moderating blocks simultaneously serve as shieldings of the operator against neutrons. The neutrons are detected with a special phosphor. In taking measurements, fast neutron sources with a yield of about $3 \cdot 10^4$ neutrons/sec can be used in these devices. The largest number of neutrons in these devices has an energy of about 5 Mev. In the moderator, the neutron energy, owing to elastic collisions, is reduced down to the thermal

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state of the moderator molecules. At room temperature, neutrons acquire the energy of the thermal state of the material (0.025 ev). A detector records with greatest efficiency precisely neutrons at this energy.

The content of moisture in samples is judged by the weakening of the flux of thermal neutrons in the sample. The moisture content in samples, in the absence of strongly absorbing elements (boron, cadmium, and so on) can be determined beginning at 1%.

The device shown in Fig. 9.1 and other similar to it are used much more often in determining elements with high neutron capture cross sections in samples (see Chapter Ten). The change in the moisture content in the samples interferes with the determination of the absorbing elements. A technique based on the attenuation in the sample of fast neutrons is used to determine the moisture of such samples. The layout of the device is shown in Fig. 9.2. To shift the fast neutron spectrum to the region 0.8-1.0 Mev, the source is placed in a steel cylinder with 5 cm thick walls (from the end). Between the steel cylinder and the sample is provided a 2 cm air gap. A 550 g sample is poured into a cylindrical cassette 10 cm in height and 6 cm in diameter. To eliminate the flux of slow neutrons, a layer of paraffin and boron is placed between the sample and the fast neutron phosphor. In order to shield the detector against thermal neutrons leaving the moderator,

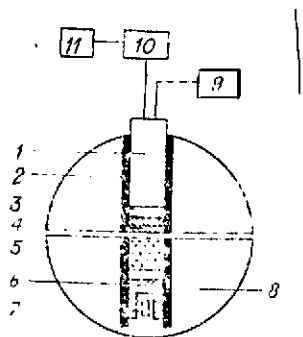


Fig. 9.2. Schematic diagram of neutron device for determining moisture of boron-containing samples by recording flux of fast neutrons (after N. I. Sotnichenko):

1. transducer with FEU-29 photomultiplier
2. cadmium shielding
3. T-40 phosphor
4. paraffin-boron filter
5. sample
6. steel shielding
7. neutron source with yield of $1.5 \cdot 10^6$ neutrons/sec
8. paraffin shielding
9. VSV high-voltage block
10. amplifier-discrimination circuit
11. PS-100 scaling circuit

the transducer is surrounded externally with a layer of cadmium. For placement and extraction of the sample, the lower block of the moderator is rotated relative to the upper block.

The dependence of the counting rate of fast neutrons for the moisture range 0.8% is linear. The absolute error of moisture determination averages 0.1%, and the relative error -- 10%. The sensitivity threshold of the method based on these data is estimated at 0.2% water.

3. Field Moisture Meters and Test Well Porosity Meters

/81

In various geological explorations, it proved to be very vital to determine soil moisture. This task is also of interest to construction men, earth specialists, and soil specialists. The classical method of determining the moisture of ground and similar materials is the thermostatic-gravimetric

method. For this purpose, in field conditions soil is sampled by the cutting ring technique (see Section 1, Chapter Four). Then the sample is brought to the laboratory, weighed, and placed in a drying oven, after which it is reweighed. Here the moisture is estimated from the difference in the weights before and after drying. This method, as we can see, is extremely simple, but very laborious and low in efficiency, especially when moisture in ground that is heavily water-logged is determined. When samples are being removed and transported, the moisture is partially lost, and thus geophysicists and geologists have long been concerned with building a device for direct determination of moisture in ground and other media *in situ*. This problem proved amenable only to neutron moisture meters containing a neutron source and detector.

Based on neutron methods, at the present time moisture meters have been developed for determining ground of moisture from measurements at the surface by means of ambulatory (portable) and hauled (vehicular) moisture meters. Moisture meters for measurements in blastholes, drillholes, and boreholes have also been built.

Rocks (sandstones, limestones, and so on), are usually filled with water at some depth from the ground level, and with petroleum in some areas. Therefore in studying test wells in areas of oil deposits an important problem is to calculate the reserves of petroleum beds. This can be done by estimating the **porosity** of rock filled with petroleum. Neutron methods are also employed in solving these and similar problems.

Fig. 9.3 shows the diagrams of several types of devices used in determining ground moisture and the **porosity** of rocks. The NVU-1 neutron universal moisture meter was built in the USSR, and the R-19 and R-21 radiometers were built in the United States. Before measurements are taken, the devices are elevated for actual media, and then the moisture and porosity of rocks are determined on the basis of these plots.

Since a large fraction of the fast neutrons is reflected from the irradiated surface in the NVU-1 insert device, a special reflector of paraffin is positioned over the source and the detector, returning some of the neutrons back into the rock. In its lower section this reflector is made of paraffin, and in its upper -- a mixture of paraffin and borax, and so on. The latter part is due to the need to protect the operator against neutrons. To check the operation of the device, a special paraffin block is included in its set. The shielding block and the testing block, when coupled, serve as a container for the source when it has been transported. The neutron source in this instrument is a plutonium-beryllium preparation with a yield of about $5 \cdot 10^4$ neutrons/sec. /83

In the R-21 device, the neutron source is a radium-beryllium preparation with a yield of $8 \cdot 10^4$ neutrons/sec. A lead and paraffin shield is provided in the instrument to protect the operator against gamma rays and neutrons. The instrument weighs 19 kg. A handle is provided for carrying the device; using the handle, the source can be shifted from the working position also into the nonworking position (within the **shield**). A reference standard unit is made in the form of a container and it is placed on special legs at some distance from the ground surface. The time for one measurement is 1-2 min.

The moisture meter is calibrated for a given type of rock taking into account all the factors, the moisture content in rocks can be determined to 0.5-1% (0.01 g/cm³). The sensitivity threshold of insert moisture meters is estimated as 1-2%.

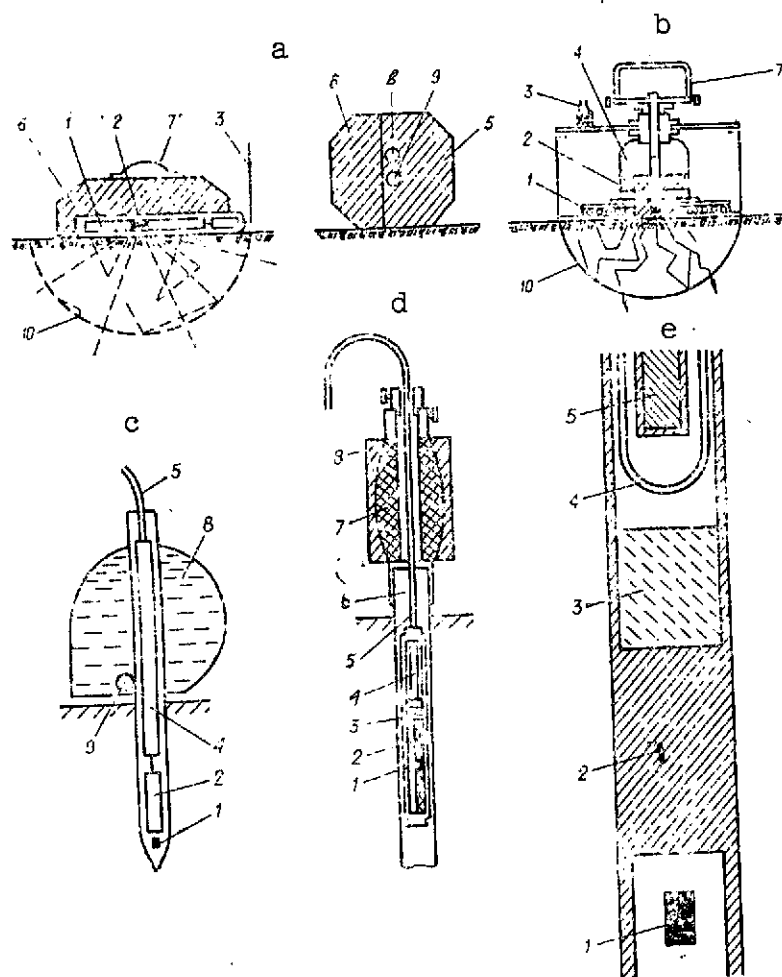


Fig. 9.3. Schematic diagram of NVU-1 portable insert moisture meter with one proportional counter (a), R-21 portable insert moisture counter with ten proportional counters (b), VNU-1 probe insert moisture meter (c), R-19 probe insert moisture meter (d), and DRST-1 test well device (e):

For a and b: 1. proportional counters
 2. neutron source
 3. cable connecting to control panel
 4. lead and paraffin shielding
 5. block of mixture of paraffin and boron-containing compound serving as shielding and part of the container

[Caption concluded on next page]

[Caption to Fig. 9.3, concluded]

6. second part of container of paraffin functioning as monitoring-calibrating device
 7. handle
 8. continuous channel for counter
 9. dead-end channel for source
 10. range of device.
- For c and d:
1. neutron source
 2. proportional neutron counter
 3. longitudinal lead shielding
 4. radio circuit
 5. cable to radiometer
 6. well casing
 7. lead section of container
 8. paraffin container
 9. insert
- For e:
1. source
 2. nickel shielding
 3. paraffin
 4. Dewar vessel
 5. LDNM neutron phosphor

Using vehicle-drawn moisture meters, the moisture of soils and the ground can be determined with a relative error of 1-1.5% when there are no hollows and depressions between the device and the rock. When these are present, the measurement error becomes greater.

Probe and test well devices are more widely used in geological investigations compared with portable and vehicle-drawn surface moisture meters. The layout of these devices is determined mainly by the arrangement of neutron source and detector. Under this principle, the devices can be subdivided into those with zero probes (the source is placed flush against the detector. And similar devices, and devices with average (20-30 cm) and large (40-50 cm and higher) probes. The above-presented NVU-1 and R-19 probe moisture meters (see Fig. 9.3 c and d) can serve as an example of devices with zero probes.

The probe unit of the R-19 moisture meter is placed in a 44 mm diameter duralumin tube, 380 mm long. The radium-beryllium source with a yield of $6 \cdot 10^4$ neutrons/sec is placed at the side, somewhat below the sensitive part of the working volume of the proportional counter, 24 cm in length. Opposite the sensitive part of the counter is placed a longitudinal lead shielding to shield the counter from the gamma radiation of the source in the probe. When the device is

being conveyed, the probe is placed within a container made of lead and paraffin. The bottom of the container is provided with a connecting piece, which during measurements is fitted onto the well casing, as shown in Fig. 9.3 d.

Probe moisture meters with small probes (about 5 cm) are used widely to determine ground moisture in penetrating-well-logging studies in SPK stations (see Section 8, Chapter Four), together with probe densimeters. /84

Ground moisture can be determined with probe moisture meters in the absence of a gap between device and rock, with a relative error of 0.5-1%. When the gap is present, the precision of the moisture measurements falls off.

To reduce the errors when determining rock moisture, devices with medium and large probes are employed. In order to measure the neutrons directly striking the detector from the rock, the space in the device between the detector and the source is filled with paraffin and lead (see Fig. 9.3 e); here the paraffin is situated near the detector, while the lead is near the neutron source. In this case the lead is needed to shield the detector from the source gamma rays and from the gamma rays produced in the inelastic scattering of neutrons -- the reaction $(n, n'\gamma)$. These shields are especially necessary for devices intended to investigate deep test wells filled with drilling mud. The absence of shielding in a device leads to its cavities being "filled" with the neutrons slowed down in the test well. The **penetration of** these neutrons in the detector interferes with the determination of the porosity of strata containing petroleum and oil. Housing the detector in a Dewar vessel enables the DRST-1 device (two-channel test well heat-resistant radiometer) to be used for studying high-temperature test wells (+120°C).

The porosity of rocks is determined with these test well devices to an average precision of +2%. A higher precision is attained when measurements are taken with devices equipped with two high-efficiency neutron detectors placed 70 and 90 cm from the source. When the ratios of the counting rates of these detectors are measured, the effect of the test well can be considerably weakened and the rock porosity can be determined to a precision of 1%.

When petroleum wells are investigated, these devices can be employed not only to determine rock porosity, but also to break through to the contact between petroleum and water in the rock. This is possible only if the stratal water includes increased concentrations of sodium chloride (common salt). Thus, in some types of oil deposits the salt content in stratal water can be 300 g/liter.

Since chlorine intensively captures thermal neutrons, the minimum rates are ascertained from the curves of the recording of neutrons opposite mineralized water-bearing strata. From the inflection of the curve, in favorable cases one can judge the contact between petroleum and water in these stratum. Since geophysicists are interested not only in moisture or porosity of rocks, but their density as well, currently devices are being developed capable of simultaneously determining all these parameters. /85

In addition to those considered here, instruments based on recording gamma rays are used to determine rock moisture and porosity (see Section 3, Chapter Eleven).

CHAPTER TEN

NEUTRON ABSORBERS

1. Capture Nuclei

There are numerous chemical elements whose atomic nuclei are capable of intensely absorbing (during capturing) slow neutrons. These elements can be divided into two groups. The first usually includes elements with high capture cross section for slow and especially for thermal neutrons: boron, cadmium, lithium, chlorine, some rare-earth elements, and so on. The second probe includes chemical elements to atomic nuclei are capable of very intensely capturing neutrons in some narrow local energy ranges, called neutron resonances. Neutron-resonant elements include silver, gold, indium, rhenium, rhodium, uranium, and so on. /86

The dependence of the capture cross section for slow neutrons on their energy can be judged from the graphs in Fig. 10.1 for several of the elements listed above. The effective cross sections of nuclear particle interaction with atomic nuclei and with the atoms themselves are usually expressed in barns ($1 \text{ barn} = 1 \cdot 10^{-24} \text{ cm}^2$).

From this figure we see that the effective cross section in the region of thermal neutrons (0.025 ev) is 756 barns for boron, 71 barns for lithium, and so on. In the resonance region with 1.5 ev energy, indium has a cross section of 27,000 barns, while silver in the region of its resonance with energy 5.23 ev has a cross section of 12,500 barns. In the region of resonance with energy of 4.94 ev, gold has a cross section of 30,600 barns, and gadolinium has a cross section of 100,000 barns in the region of resonance with energy 1.93 ev (this is the highest neutron cross section). Rock-forming chemical elements have effective cross sections for slow neutrons that vary within the range of several barns. This indicates the possibility of determining the content of elements with high cross sections from the absorption of neutrons in rocks.

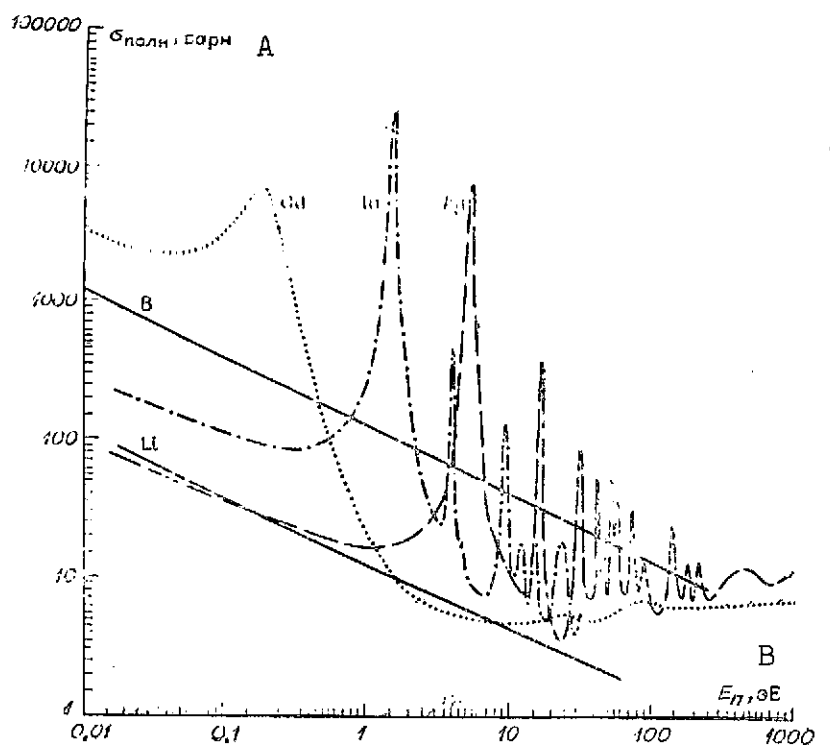


Fig. 10.1. Dependence of the effective cross sections of boron, lithium, cadmium, indium, and silver on slow neutron energy

Key: A. σ_{tot} , barns

B. eV

2. Boron Determines Itself

Boron is one of the chemical elements finding wide use in various branches of the national economy. Thus, in medicine compounds of boron in the form of boric acid are used as disinfectants. In agriculture, trace additions of boron are widely used as fertilizers. The ability of boron to intensely capture slow neutrons is used in atomic technology for neutron shielding (boron-containing compounds are added to moderators). Boron rods are widely used in controlling the operating conditions of nuclear reactors and for other purposes. Recently, boron-containing compounds have also begun to be employed as high-efficiency rocket fuel, and so on.

Owing to the high importance which boron has in industry and agriculture, every industrially developed country is in constant need of replenishing its reserves of boron, therefore no small amount of attention is given to geological exploration for boron. In the initial stage of the exploration, geologists were compelled to collect a large number of rock samples for their subsequent chemical analysis in the

laboratory. Later, geophysicists used the absorbing properties of boron to determine it in rocks.

The capture of neutrons by boron is accompanied by the escape from the nuclei of charged alpha-particles. This property of boron, as already noted in Section 2, Chapter Two, is used in making proportional and scintillation neutron counters. From the effects caused by alpha-particles in counters, one can evaluate fluxes of neutrons, which are electrically neutral particles.

Geophysicists also used these neutron counters to make various devices for determining boron in natural compounds.

Thus, we have an unusual paradox: boron contained in neutron counters essentially serves to detect boron that is present in mineral formations of rocks. Building neutron laboratory devices made it possible to avoid the expensive and laborious chemical analysis.

However, here we must somewhat interrupt our account of how boron searches for itself. The point is that besides boron, several other nuclei of chemical elements exhibit an intense ability for neutron capture, in particular, lithium; when its nuclei capture neutrons, alpha-particles and a tritium (superheavy hydrogen) nucleus is also produced. From the effects caused by these particles in scintillation counters neutrons are also recorded and boron determined in rocks. Recently, high-efficiency neutron proportional counters filled with helium (helium-3) have begun to be used. This is an isotope with an effective cross section of 5060 barns. The effectiveness of these counters is 4-5 times higher than the effectiveness of counters filled with boron trifluoride. Helium counters can be **resorted** to also when determining boron in rocks.

Devices of the type shown in Fig. 9.1 are used as laboratory units. When samples weighing 50-100 g are analyzed with these devices, boron concentrations beginning at 0.02% and higher can be determined, and when analyzing 2-3 kg samples -- 0.003% and higher. Neutron devices can be used for determining even other chemical elements in samples, with the following sensitivity thresholds: 0.1% for lithium, 0.01% for cadmium, 0.0005% for gadolinium, and so on.

Devices of the type shown in Fig. 9.1 are used in analyzing samples whose boron content usually does not exceed 6%. At higher boron concentrations in samples, boron nuclei capture virtually all the neutrons striking the sample, and the device begins to record only background radiation. Therefore special procedures must be used to determine high boron concentrations in samples; these procedures are examined below.

There is no need to describe this chemical element for the reader. We refer those more interested to a book by M. M. Maksimov, published in 1970. Above it was noted that this element has specific properties with respect to neutrons. In the 5.23 ev energy range, atomic nuclei of the isotopes silver-109 have a resonance cross section. Neutron capture **at this and other energies** forms the radioactive isotope silver-110, produced in the reactions $\text{Ag}^{109}(n, \gamma) \text{Ag}^{110}$. On disintegrating (half-life $T = 24.2$ sec), the isotope emits beta-particles with energy $E_\beta = 2.24$ Mev (60%) and 2.82 Mev (40%), and gamma-quanta with energy of 0.656 Mev (60%).

If a silver foil is surrounded with a cadmium layer of about 1 mm thick, the foil is activated mainly by the neutrons in the silver resonance region. Thus, on placing the silver foil surrounded with cadmium in a flux of neutrons for an irradiation time t_0 not more than $5 T = 2$ min, by measuring the induced activity of silver-110 one can judge the fluxes of neutrons with energy in the region 5.23 ev. The induced activity is measured with gas-discharge or scintillation counters by recording the beta-particles or gamma-quanta, or from the overall flux of these particles. Similarly using a foil and other shapes made of other materials, one can build detectors to measure the resonant neutrons in other energy regions. These neutron detectors are called activation detector in nuclear physics.

We can judge resonant neutron fluxes also by recording gamma-radiation from the radiation capture of neutrons -- the reaction (n, γ) . When neutrons are **captured** by silver-109, gamma-quanta with energies of $E_\gamma = 0.268$ Mev (12%) and 0.4-0.5 Mev (with a maximum at 2.2 Mev) and other harder lines are produced. Since this radiation is generated instantaneously during neutron capture, it can be measured with a gamma-spectrometer during neutron capture. Similar gamma-radiation arises when neutrons are captured by the nuclei of atoms of several other elements with resonant cross sections. In contrast to activation detectors, these detectors are called radiation detectors and are used much less often, owing to the difficulty of recording gamma radiation of radiative capture against the background of analogous radiation from cadmium and other materials capturing slow neutrons.

A foil of silver and other materials can be used not only in recording resonant neutrons but also for discriminating them against the background of neutrons with other energies. Essentially, this process is illustrated by Fig. 10.2. If in the path of a flux of neutrons escaping from a moderator one places a cadmium filter, it will absorb virtually all the neutrons with energies from 0.4 ev and below and will admit neutrons with higher energies. By placing /89 a foil of a neutron-resonant element in the path of these neutrons, one can deform the spectrum of epithermal neutrons. The foil will

"eat up" the neutrons in the region of its resonance. A reduced neutron flux will be observed in the region of these energies in the flux of episcadmium neutrons. If then from the results of measuring the flux of episcadmium neutrons one subtracts the second measurement corresponding to the deformed neutron flux, the resulting value would correspond to the measurement of the neutron flux in the isolated resonant energy region. Thus, by irradiating the material under study twice with a flux of episcadmium neutrons and with neutrons additionally passed through the resonant absorber, we get the resulting difference effect apparently corresponding to irradiation of the medium under study with a flux of resonant neutrons.

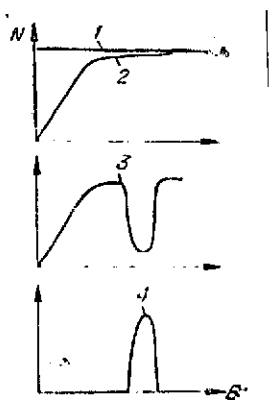


Fig. 10.2. Schematic dependence of neutron flux on energy:

1. flux of slow neutrons (arbitrarily shown identical for neutrons of all energies)
2. flux of energies admitted through cadmium
3. flux of neutrons admitted through cadmium and resonant filter
4. isolated neutron flux -- difference value obtained when subtracting curve 3 from curve 2

A method of determining the content in samples of silver and other elements with high resonant cross sections for neutron capture was developed on this principle and the Institute of Geology and Geophysics, Siberian Branch, USSR Academy of Sciences. The principle of the method is clear from Fig. 10.3. If the silver content is determined in the sample, the resonant filter and the activation detector are also made of silver. This is necessary to cancel out the effect of other resonant elements present in the sample. Thus, foils containing silver usually also contain indium, which also has a high resonant cross section. In the event that there is no other element with a high resonant cross section in sample, the work can proceed without the resonant filter in the device. Here the silver in the samples is determined by the method of single irradiation.

Thus, based on this technique silver is capable of determining itself. In a similar fashion, other elements whose atomic nuclei are capable of absorbing neutrons in some local energy regions can determine themselves.

At the present time a long series of neutron-resonant devices have been developed for determining the content in samples of various elements with high resonant neutron capture cross sections. Their schematic layout

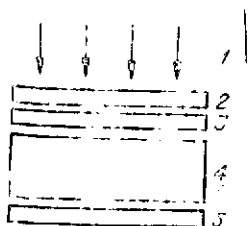


Fig. 10.3. Scheme explaining the neutron resonant principle of sample analysis:

1. flux of neutrons escaping from moderator
2. cadmium
3. resonant filter
4. sample containing the resonant element being determined
5. activation detector

can be seen in Fig. 10.4. Neutrons slowing down in the hydrogen-containing medium enter the inner cavity and pass through cadmium. In the second measurement, a resonant filter of the element being determined is placed during the sample and the cadmium. Disk-shaped inserts are needed to absorb neutrons heading toward the activation foil-detector from the ends. The extraction of the foil-detector from the cavity after activation is carried out with a remote control lever. The foil detector and insert (for **extraction**) can be coupled mechanically or with a magnet. The removed foil detector is fitted onto a gas discharge counter, which measures its induced activity. In quantitative measurements of the element determined, the foil irradiation time t_0 , the time during which the activation detector is being transferred t_{tr} , and the time required to measure its induced activity t_{in} are selected quite specifically.

To automate the process of advancing the foil-detector from the irradiation site to the counter, a cylindrical channel is made in the moderator beneath the foil-detector. After the foil has been irradiated, the electromagnet is switched off. Under the action of gravity, the foil slides downward and settles on the gas-discharge counter. Using this neutron-resonant method, when making measurements with two sources with a total yield of 1.10^7 neutrons/sec, it became possible to determine in samples silver and rhodium with a sensitivity threshold of 0.015 and 0.02%.

Similarly, the content in samples of other neutron-resonant elements can be determined. Some of these elements have unfavorable neutron-activation properties: the absence of a radioactive isotope in general, as for example for dysprosium, or a relatively long half-life, as for example in gold-198 ($T = 2.7$ days), and so on. To determine these elements in samples, overlapping of the resonances of dysprosium ($E_p = 5.35$ ev) and gold ($E_p = 4.94$ ev) with silver can be used, and thus based on silver one can determine the content of these elements in samples with sensitivity thresholds of 0.3 and 0.7%, respectively. Similarly, based on rhodium the content in samples of indium with a 0.06% sensitivity threshold is determined.

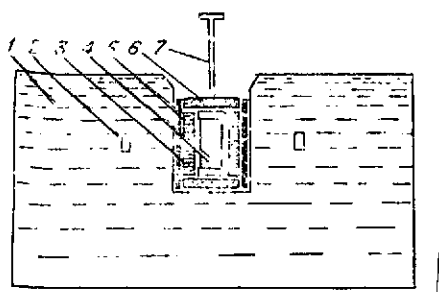


Fig. 10.4. Neutron-resonant device:

1. neutron moderator (water or paraffin)
2. neutron source (two)
3. sample in annular cylindrical beaker
4. cylindrical foil detector
5. cylindrical cadmium filter
6. insert with neutron-resonant element being determined (two)
7. remote control pin-lever

2 and 3%, respectively. This technique can be used also in determining in samples extremely high concentrations of these elements (all the way to 100%) with a relative error of about 1%.

4. Insert Boron Meters for Field Measurements

The task of searching for boron deposits and their prospecting can be solved most effectively by developing field instruments capable of determining the content of this element directly in the field -- at the rock outcropping. This is necessary for searching for boron deposits is dictated also by the following factor. Mineral formations of boron, which are the principal source of its raw material, visually are poorly differentiated from other natural compounds. Therefore developing instruments "seeing" boron in rocks is exceptionally vital. Accordingly, in the Institute of Geology and Geophysics, Siberian Division, USSR Academy of Sciences, the goal was formulated of building a light portable insert instrument which geologists could take on expedition with them in searching for the mineral raw material and in prospecting for boron in pits and mines. At the present time such instrument has been built with a scintillation boron detector weighing about 4 kg (Fig. 10.5) capable of determining at rock outcroppings boron content from 0.2 to 7%.

These neutron-resonant devices with activation detectors have found one more field of use, namely: using them, it became possible to determine the content in samples of such absorbing elements as boron, lithium, and so on.

Work with the silver detectors established that using this technique of recording the total neutron flux (without cadmium), one can determine the content of boron and lithium in samples with a sensitivity threshold of 0.01 and 0.07%, respectively. By recording epicadmium neutrons, boron in natural materials is determined in the presence of lithium with a sensitivity threshold of 0.1%. By the technique of combination measurements without the cadmium filter and with it, separate determinations can be made of boron and lithium in samples with a relative error

Employing these devices in practice means a considerable rise in the effectiveness of **exploration** and prospecting for boron and reduction of their costs. Here it is not necessary to systematically take rock samples for their laboratory analysis. Before development of the insert device, as already noted, the laboratory technique was the only method of determining boron in rocks. When working with the insert boron meter, the sampling technique does not become entirely necessary. It is essential in calibrating the instrument and in making control measurements. However, the number of samples is very low compared to the total number of measurements.

In order to detect boron mineralizations lying far beneath the surface, it is important to discover at the ground surface even lower boron concentrations. Accordingly, in the Institute of Geochemistry and Analytical Chemistry, USSR Academy of Sciences, imeni V. I. Vernadskiy, under the supervision of Professor V. I. Baranov (Moscow), a device (weighing about 8 kg) was built which can see low boron concentrations in rocks from 0.003 to 0.2%. In addition, devices for motor vehicular searching for boron in rocks beginning at 0.003% have also been developed under the supervision of V. I. Baranov.

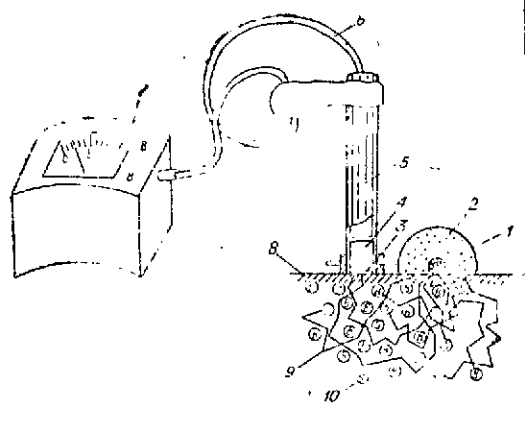


Fig. 10.5. Schematic diagram of insert boron meter:

1. neutron source
2. hydrogen-containing paraffin reflector of neutrons, simultaneously serving as shielding for the operator
3. boron-containing scintillator
4. photomultiplier
5. transducer case
6. cable
7. instrument panel carried by the operator on his chest (secured with a belt)

Using this insert device, in bedrock outcroppings, besides boron, lithium, mercury, rare-earth elements, and so on can also be determined.

5. Boron Meters for Studying Boron Test Wells

In searching for boron deposits far beneath the ground level, test wells are drilled in the areas of their assumed location and cores are extracted from the wells by means of drilling casings. The boron content in the cores can be judged only from laboratory analysis. This method of detecting boron in rocks drilled with test wells is highly laborious.

V. I. Baranov et al. proposed that devices with neutron sources and detectors be used for determining

Fig. 10.5. [Continuation]

- 8. rock studied
- 9. trajectories of slowing down neutrons
- 10. boron

boron¹ in rocks based on test well profiles. The layout of this device is similar to the one used in determining the porosity of rocks (see Fig. 9.3 c).

Currently it has been established that depending on the type of intervening rock, boron in the rock can be determined beginning at concentrations of 0.003 to 0.03%. In dry test wells, by recording the flux of thermal neutrons, one can determine boron to concentrations not higher than 4-5%, and in test wells filled with water (or drilling mud), the boron content is determined to concentrations of 1-1.5%. By recording epithermal neutrons using a detector dropped in cadmium, the upper limit of the device can be raised 1-2%. Boron reaches high concentrations in rocks (13-20%); at this level it captures virtually all thermal neutrons. The device can record only the background radiation, that is, neutrons travelling to the detector through the test well and through the device. Therefore the boron concentrations in the above-indicated rocks differ by identical values. Here high boron concentrations in rocks are determined only with a neutron-resonant technique, in particular, by recording the neutrons in the region of silver resonance (5.22 ev). The cross section for boron in this energy range drops to 54 barns (see Fig. 10.1). Compared with rock-forming elements, this cross section is not very large, but is still adequate in order to judge the boron content in rocks. High concentrations of borons in rocks is determined usually with scintillation gamma-counters wrapped in a silver layer. The neutron fluxes in the region of silver resonance can be evaluated by recording the gamma radiation of radiative capture.

493 /

6. Determination of Other Neutron Absorbers in Studying Test Wells

This neutron technique was resorted to in determining mercury, rare-earth elements, cadmium, and so on. Since change in the moisture of rocks interferes with the determination of these elements, the investigations were conducted by placing in the well-logging device two neutron sources at different distances from the detector. Or by measuring simultaneously the flux of thermal and epithermal neutrons. Similar procedures were used also in determining boron in rocks with variable moisture.

Thus, when monomineral ores are investigated for mercury, its content can be determined -- using the two-source technique -- with a sensitivity threshold from 0.08 to 0.3%, depending on the material composition of the rock. Integrated mercury-arsenic, mercury-antimony, polymetallic, and other ores are investigated with the additional employment of these two-source selective

gamma-gamma technique (see Section 3, Chapter Six). The mercury content in ores can be determined by this integrated method with a sensitivity threshold of 0.03% when the measurement results are averaged over meter intervals.

Rare-earth elements can be determined with a sensitivity threshold from 0.003 to 0.01% when the flux of thermal and epithermal neutrons is measured, depending on the material composition of the intervening rocks and ores. A similar technique is used in determining the content in polymetallic ores of cadmium, with a sensitivity threshold of 0.04%. The presence of a correlation between cadmium and zinc made it possible by this technique to determine the zinc content, which has no anomalous properties with respect to neutrons. /94

In addition to the foregoing, this technique is used when determining high concentrations of manganese (from 5 to 10% and higher) and iron (from 10-15% and higher) in rocks.

CHAPTER ELEVEN

GAMMA RAYS STRUCK OUT BY NEUTRONS

1. Reactions Leading to the Generation of Gamma Rays

In section 3, Chapter Ten, it was noted that under the effect of slow neutrons, the reaction (n, γ) -- radiative capture of neutrons -- occurs. Nuclei of atoms of all chemical elements, except for helium-4 nuclei (alpha-particles) participate in this reaction. The reaction (n, γ) occurs with highest probability at neutron energies from 10 ev and below. In this energy range, the reaction probability predominates over the probability of the elastic scattering of neutrons. The gamma radiation generated can vary over quite wide energy limits -- approximately from 0.2 to 11 Mev. Each isotope is characterized by the formation of gamma-quanta with a specific spectrum. From the recording of gamma-quanta of this spectra, we can judge the nature of the nuclei of the atoms participating in the reaction (n, γ) .

The striking out of photons (gamma rays) under the effect of neutrons can occur for a long series of atomic nuclei also in the reaction $(n, n' \gamma)$ -- inelastic scattering of neutrons. In contrast to the reaction considered above, this reaction occurs only under the effect of rapid neutrons with energies 0.6-1 Mev and higher. And the higher the neutron energy, the greater the probability with which the reaction $(n, n' \gamma)$ occurs. The energy of the gamma-quanta induced in this reaction does not exceed 7.1 Mev. However, each atomic nuclei of an isotope is characterized by the formation of gamma-quanta with a specific energy. In spectrometric measurements, we can judge the nature of the atomic nuclei participating in the reaction $(n, n' \gamma)$.

The occurrence of the reactions $(n, n' \gamma)$ and (n, γ) differs with respect to the time interval in which the neutrons are slowed from fast (1-11 Mev) to epithermal (about 1 ev). This time interval can vary from fractions to tens of microseconds. Short slowing down times correspond to hydrogen-containing media and media containing high concentrations of elements with large slow neutron capture

cross sections (boron, gadolinium, and so on). Longer slowing down times correspond to sandstones, limestones, and other rocks. /95

When working with isotopic neutron sources continually emitting fast neutrons ($E_{av} \approx 5$ Mev), it is possible to differentiate the reaction $(N, n'\gamma)$ from the reaction (n, γ) only when irradiating small samples, whose dimensions are inadequate for the total neutron slowing down process to occur. In the remaining cases, processes associated with these reactions are very difficult to differentiate.

Based on the reactions we have considered, laboratory methods of analyzing rocks and ores are implemented. However, methods based on these reactions are used much more widely in studying profiles of test wells. Recently, the possibilities of these methods as applied to studying benthic marine deposits rich in various minerals have come to light.

2. Neutron Gamma-Analyzers of Samples

By the gamma-radiation of the inelastic scattering of neutrons, iron in ore samples is determined. A schematic diagram of a neutron gamma-device used for these purposes is shown in Fig. 11.1. The plutonium-beryllium source used has a yield of $1 \cdot 10^6$ neutrons/sec. The sample is placed in $30 \times 20 \times 3$ cm³ cassettes. In order to cancel out the effect of gamma-radiation in the radiation capture of neutrons, the device must be placed far from massive objects that can produce an interfering background (by radiation being scattered from them, and so on). Iron in the samples is determined from the recording of 0.84 Mev gamma radiation. The measurement error was estimated at 1.6 percent.

The neutron gamma-method in which gamma-radiation of the radiative capture of neutrons is recorded is applied in determining ten elements with sensitivity thresholds from 0.1 to 5 percent.

Rock-forming elements can be determined, beginning at concentrations of 1-5 percent. and metallic minerals -- beginning at 0.1-0.5 percent. These sensitivity thresholds are obtained with a device schematically shown in Fig. 11.2. In order when recording radiation from the reaction (n, γ) not to have interference from the reaction $(n, n'\gamma)$, the following technical procedures are used. /96 When recording gamma-quanta with energies higher than a 6.1 Mev induced in the reaction $(n, n'\gamma)$ in oxygen, the measurements are taken with polonium or plutonium-beryllium sources ($E_n = 1-11$ Mev) with a yield of about $5 \cdot 10^5$ neutrons/sec. When necessary to record gamma radiation with energies higher than 3.8 Mev, the measurements are made with a polonium-boron source ($E_n = 1-5$ Mev) with a similar neutron yield.

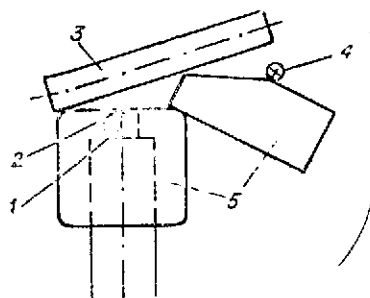


Fig. 11.1. Scheme of device for analyzing iron in samples based on recording the gamma radiation from inelastic scattering of neutrons (dimensions in centimeters):

1. Detector
2. 2 mm lead filter
3. Sample
4. Neutron source
5. Lead

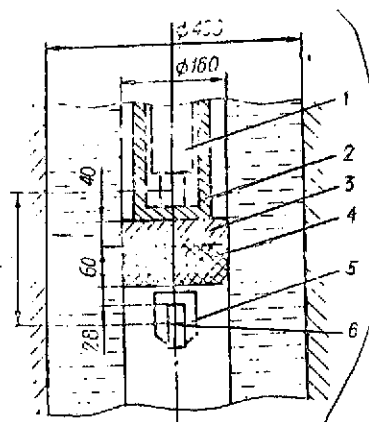


Fig. 11.2. Neutron-3 device for measurements of gamma radiation in the radiative capture of neutrons (dimensions in millimeters):

1. Transducer
2. Boron carbide (B_4C)
3. Paraffin
4. Test sample
5. Lead
6. Neutron source

With the same measurement technique, one can determine the cadmium and boron content in samples, with a 0.03 percent sensitivity threshold. Cadmium is determined by the reaction (n, γ) , and boron -- by the reaction $B^{10}(n, \alpha) Li^7 + \gamma$. The gamma-radiation with 479 kev energy produced in the last reaction is emitted just as instantaneously as the gamma radiation generated in the reaction (n, γ) .

3. Field Neutron Gamma-Moisture Meters and Test Well Porosity Meters

In Section 3, Chapter Nine, it was noted that a technique based on recording slowing-down neutrons is used widely in determining rock moisture and porosity. The captured gamma-radiation considered in this chapter is also associated with slowing-down neutrons. Therefore, by recording the total flux of captured gamma-radiation, one can also judge the moisture and porosity of rocks.

In 1941 a gamma-method was proposed by Academician B. M. Pontecorvo for determining the porosity of rocks to neutrons. This date essentially refers to the birth of that part of nuclear geophysics that is based on using radiation from radioisotope sources.

An intensimeter with gas-discharge and scintillation counters is used in measuring the total flux of the gamma-radiation being recorded. Accordingly, this method of determining rock moisture and porosity came to be called the intensimetric method.

Whereas in the first stage generally a method based on measuring only gamma-radiation of rock was used in determining moisture and porosity, recently in general a technique based on recording overall fluxes of gamma rays and neutrons is used in solving these problems. The fluxes of these radiations are measured with ordinary gamma counters covered with a layer of cadmium about 1 mm thick. The cadmium freely admits to the detector the capture gamma-radiation of rocks without weakening it. Also, the cadmium intensely captures thermal neutrons bearing information on rock moisture or porosity. When cadmium captures neutrons, gamma-radiation is also released, acting on the detector. Thus, gamma-ray detectors wrapped with cadmium afford an evaluation of overall fluxes of gamma-rays and neutrons. We can judge the design of devices used in recording just gamma-radiation and overall fluxes of gamma-rays and neutrons from the data in Fig. 11.3. To protect the detectors against direct gamma-radiation of the neutron source, between them is placed a composite shield of iron (250-300 mm) and lead (90 mm). Placement of the scintillation counter in a Dewar vessel makes it possible, using the DRST-1 (see also Fig. 9.3 e) device, to investigate high-temperature wells (up to $+120^{\circ}\text{C}$). For protection against activation by neutrons, the scintillator is enveloped with a composite filter of boron, lead, and cadmium. The lead filter is needed to suppress gamma-radiation arising in the boron capture of neutrons, and the cadmium filter is needed to absorb the characteristic radiation induced in lead under the effect of gamma-quanta. In the SP-62 well-logging device for simultaneous recording of the flux of gamma-rays and thermal neutrons, the gas-discharge counters are enveloped in a 0.5-0.7 mm cadmium layer. /97

Rock moisture and porosity can be determined more reliably using instruments that simultaneously record flux of gamma-rays and neutrons. Rock porosity in the 5-40 percent can be determined with a relative error of ± 10 percent, that is, with an absolute error of 0.5 and 4 percent.

Also resorted to in determining soil moisture is an instrument with gas-discharge counters using a cadmium filter -- the NIV-1 (neutron moisture meter). The moisture of soils in the 2.5-40 percent range is determined to an absolute precision of ± 2 percent. /98

These devices can be used in oil-field geophysics to find oil-bearing strata and to differentiate them from mineralized water-bearing strata. Besides this, this technique and equipment is used in finding gas-bearing strata.

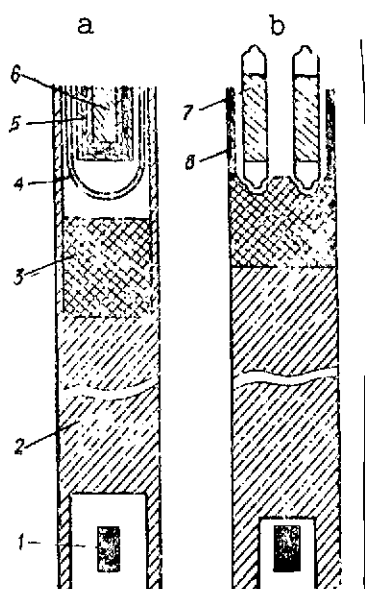


Fig. 11.3. Diagram of probe portion of depth devices of the DRST-1 (a) and SP-62 (b) types, used in oil-field geophysics to record fluxes of gamma-rays and overall fluxes of gamma-rays and neutrons, respectively:

1. Neutron source
2. Iron shield
3. Lead shield
4. Dewar vessel
5. Layered filter
6. Phosphors
7. SI-23G gas-discharge counters
8. Cadmium filter

In studying coal-prospecting wells, these intensimetric methods are resorted to in finding coal strata in porous wells. Besides this, using the intensimetric modification of the neutron gamma-technique, boron-bearing strata in well profiles can be discovered. This technique in concert with other methods also is used in discriminating salt-bearing beds -- in order to differentiate potassium salts from sodium salts, and so on.

4. Determination of Several Ore Elements with a Natural Rock Bedding

Above it was noted that gamma radiation struck out by fast and thermal neutrons has a characteristic spectrum for each chemical element. Therefore as soon as geophysicists were able to devise a gamma-spectrometer, they at once began developing this technique of determining a long series of minerals in rocks and ores. At the present time this technique has been developed for determining the metal elements listed in Table 3. As we can see, here chromium and iron are determined, beginning at a few percent, while nickel, copper, and mercury are determined starting with fractions of a percent.

These elements are determined by recording hard gamma-radiation traversing a considerable path in the rock. This makes it possible to secure information about a rock layer 10-15 cm in thickness. When recording softer radiation, elements are determined in considerably thinner rock layers. Thus, above it was noted that in the selective gamma-gamma-method, the roentgen-radiometric method, and the method based on the Mossbauer effect, in general radiation with energy not above 100 kev is recorded. Radiation with this energy can leave a rock layer no more than 5 mm thick. Accordingly, the neutron gamma-method, being capable of greater depth compared with the other gamma-methods examined, came to be intensively introduced into geological practice.

With the development of the spectrometric neutron gamma-method, it also became possible to determine the ash content of coals in well profiles, which was already discussed in Section 4, Chapter Five. Compared with the intensimetric method, the spectrometric method permits finding the contact between oil-bearing and mineralized water-bearing strata more reliably.

/99

TABLE 3
POSSIBILITIES OF DETERMINING SEVERAL MINERALS IN ROCKS BASED ON
RECORDING GAMMA-RADIATION OF THE RADIATIVE CAPTURE OF NEUTRONS

| Element Determined | Mass macro- scopic cross section, cm ² /g | Energy range of radiation measured, Mev | Sensitivity threshold | Remark |
|-----------------------|--|--|--------------------------|---|
| Titanium | 0.073 | 3.0-4.6 | -- | Iron must be determined in complex titanium iron ores |
| Chromium | 0.035 | 3-5 and higher | 4-5 | Calibrated graph is linear for the 0-10 ⁰ range |
| Manganese | 0.143 | 4.8-6.0 6.2-10 | -- | Determined in ores of carbo- nate composition in the 0-15 per- cent range |
| Iron | 0.027 | 4.0-6.2 6.4-9 | 5-6 | Calibrated graphs are linear for the 0-25 percent range |
| Nickel | 0.046 | 8.6-9 7.4-8.2 | 0.5-0.7 | Calibrated graphs are linear for the 0-3 percent range |
| Copper | 0.035 | 3.0-6.6 6.8-9.0 | 0.2-0.7 | Copper sand- stones |
| Mercury | 1.08 | 7.2-10 5.4-6.4 Along the 6.44 and 5.99 lines | 0.2-0.7 0.1 | Pyrite ores |

Building semiconductor well-logging detectors will permit extending even further the capabilities of these spectrometric techniques. Existing laboratory semiconductor detectors are used in experimental investigations to find their capabilities in searching for minerals at the bottom of seas. In these investigations, it was established that using an instrument

with a source emitting 10^8 neutrons/sec, gold can be determined in benthic deposits in amounts from $8 \cdot 10^{-4}$ percent and higher. In addition, using this technique one can determine a long series of other minerals in benthic deposits -- manganese, silver, and so on.

In the exploration, the equipment for benthic investigations /100 is suggested to be placed in special bathyscaphes, lowered to the bottom, or in submarines -- with the submarines immersed at the bottom.

CHAPTER TWELVE

EXPELLED NEUTRONS

1. How Can Neutrons Be Expelled From Atomic Nuclei?

Under the action of nuclear radiation from radioactive isotopes, neutrons can be expelled (driven out) from the nuclei of atoms of certain chemical elements. Gamma-rays and alpha-particles serve as the bullet expelling the neutrons. Their interaction with matter leads to the reactions (γ, n) and (α, n) . Methods based on these reactions are called, respectively, gamma-neutron (photoneutron) and alpha-neutron techniques. Gamma-rays, compared to alpha-rays, exhibit the highest penetrating ability. Therefore the gamma-neutron method in nuclear physics is used much more broadly than the alpha-neutron method.

Under the action of gamma-radiation from radioisotope sources with energies not higher than 3 Mev, neutrons can be expelled only from the nuclei of beryllium and deuterium. The thresholds of this reaction or the nuclei of atoms of these elements are 1.67 and 2.23 Mev, respectively. If the energy of the gamma-quanta will be lower than their thresholds, it is impossible to use them to drive out neutrons from the nuclei of these elements.

2. Laboratory Beryllometers

Natural beryllium consists of one stable isotope with mass number 9 (100 percent). Its mean content in the earth's crust by weight is $3 \cdot 10^{-4}$ percent. The most widely distributed source of beryllium ores is the mineral beryl, $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$, containing 5 percent beryllium. Ores with a minimum beryllium content 0.01 to 0.1 percent are regarded as commercial, depending on the scale of the deposits and the economic conditions of their exploitation.

Of the isotopic preparations for beryllium determination, use is made of the gamma-radiation of antimony-124 ($T = 60$ days, $E_\gamma = 2.11$ Mev, 9.9 percent), 1.71 Mev (45.7 percent)). Thus, for each 100 decay acts of antimony-124, 55.6 percent photons are produced, which can lead to a photoneutron reaction with beryllium.

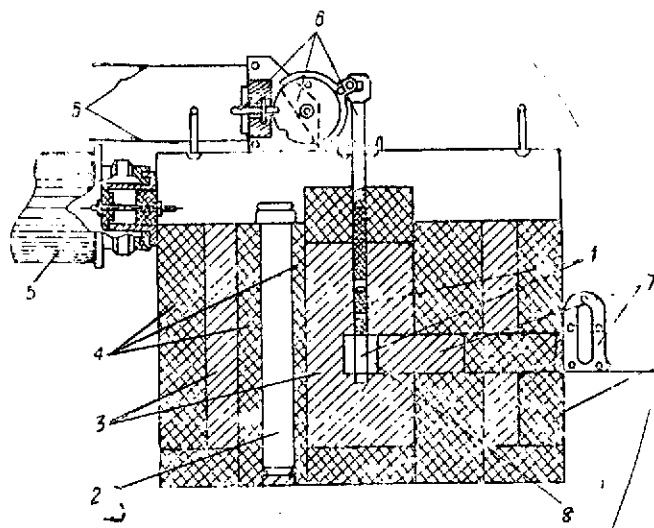


Fig. 12.1. Design of FNUV-4-59 (ROB-1) photoneutron device:

1. Gamma-radiation source
2. Proportional neutron counter
3. Lead shield
4. Paraffin moderator
5. Preamplifier cascade
6. Accessory for remote control of source
7. Accessory for inserting and retracting samples
8. Sample cassette

The photoneutron method for /101 beryllium analysis in samples was proposed in 1937 by G. V. Gorshkov (Leningrad). A long series of beryllometers with proportional and scintillation neutron counters was built for this purpose in the USSR and abroad.

The design of photoneutron devices with proportional counters can be evaluated from the example of one of the first devices built in the USSR in the All-Union Institute of Prospecting Geophysics (Figs. 12.1 and 12.2). A 50 mcurie source is used in the unit. Slowing down neutrons are recorded with four proportional counters filled with boron trifluoride. Subsequently, in place of the ROB-1 radiometric beryllium finder, a similar unit, the ROB-1M (Berill-1) with six counters began to be built. In the ROB-1, the inner lead shield 3.5 cm thick surrounding the sample is designed to shield the detectors from gamma-radiation. The amplitude of pulses caused by neutrons, even though exceeding the amplitude of pulses caused by gamma-rays by a factor of 7-10,

when the latter have a high intensity the amplitude of the impulses are superimposed, and eliminating them is impossible with the ordinary system of discrimination. Therefore in order to reduce the flux of gamma-radiation in instruments of this type, lead /102 shielding of counters is used. The outer lead shield is intended to protect operating personnel. The thickness of the moderator layer is 10-11 cm, that is, quite adequate to slow the neutrons produced down to thermal energies. The cassette has a 40 cm³ capacity and is designed to be filled with samples weighing 50 g.

Before inserting or removing a sample, the source is shifted into the upper position with a remote control device, and when measurements are being taken it is shifted into the lower position (in the sample center). Using the ROB-1, samples can be analyzed for beryllium with a $7 \cdot 10^{-4}$ percent sensitivity threshold.

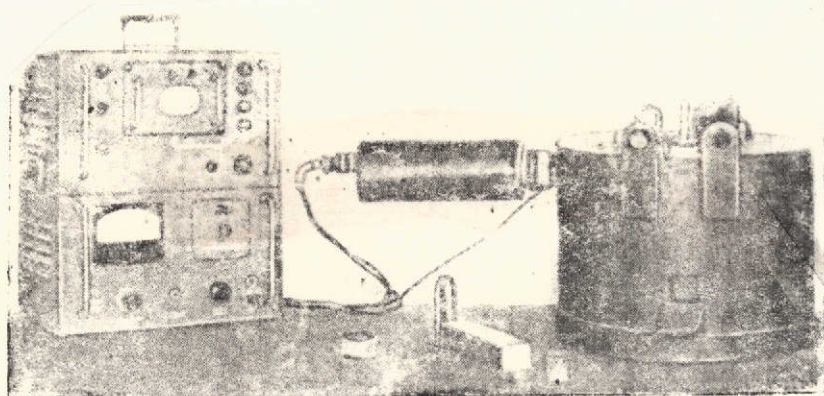


Fig. 12.2. External view of FNUV-4-59 photoneutron device

P. O. Klevtsov and B. I. Polyakov (VIRG) built a high-sensitivity device with a 200 mcurie source and containing 20 proportional boron counters to determine low beryllium concentrations ($2 \cdot 10^{-5}$ percent and higher) in metallometric and other samples. Replacing these counters with helium counters will mean an approximately fivefold reduction in source activity.

A. L. Yakubovich et al. built the Berill-2 device with scintillation counters for analyzing powdered samples. The unit can be used in two modifications (Fig. 12.3): for analyzing powdered samples and ore chunks (large). The T-1 or T-2 disk scintillators and the FEU-49 photomultiplier can be used as the neutron phosphor in the device. A 10-20 mcurie antimony-124 preparation serves as the radiation source. The weighed powdered sample is 100 g. The weight of the chunk samples can vary from 100 to 1000 g. The vessel is 25 cm in diameter and 20-30 cm high. The sensitivity threshold is estimated at $5 \cdot 10^{-4}$ percent when powdered samples are analyzed, and $3 \cdot 10^{-3}$ percent when chunk samples are analyzed.

In determining beryllium in samples, the photoneutron method is capable of increasing the capacity of the analysis by a factor of 3-5 compared with the spectral method, and by a factor of 4.5-5.7 compared with the chemical method. The cost of each analysis for beryllium with the photoneutron method is 32-83 kopecks, two to seven times cheaper than the spectral analysis, and 3.3-11 times

cheaper than the chemical analysis. The photoneutron technique of determining beryllium in samples is vital in analyzing samples collected for exploratory and prospecting of beryllium deposits. It stands to reason that devising a technique for determining beryllium directly in bedrock will mean an even greater operational capacity and cost reduction. Section 4 of this chapter discusses field beryllometers.

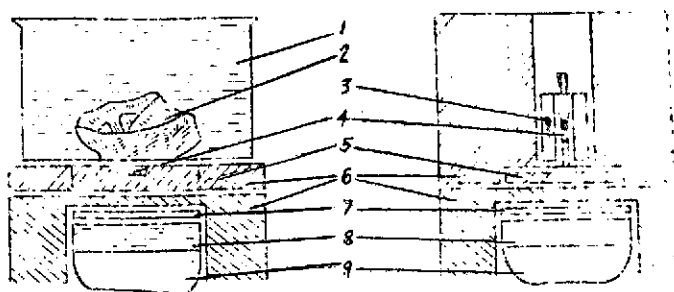


Fig. 12.3. Design of scintillation beryllometer for analyzing chunk (a) and powder (b) samples:

1. Vessel containing water (moderator)
2. Chunk sample
3. Cassette containing powdered sample
4. Source of gamma-quanta
5. Lead shield
6. Paraffin moderator
7. Neutron phosphor
8. Light guide
9. Photomultiplier

3. Laboratory Deuterium Meters

In natural objects, the primary source of deuterium is ordinary water, where the deuterium content in the hydrogen averages 0.015 percent. In the view of some investigators, in petroleum the deuterium content can exceed its content in water by about twofold. The first studies on determining deuterium in water were conducted in Great Britain by K. P. Haig, who published his studies in 1953 and 1954. In the USSR, the first work was done by V. I. Baranov et al. in the Institute of Geochemistry and Analytical Chemistry (GeoKhI), USSR Academy of Sciences.

Usually the isotope sodium-24 ($E_\gamma = 2.76$ Mev (100 percent)) is used as the gamma-radiation source for the photofission of deuterium. Its low half-life ($T = 15$ hours) is a major disadvantage of this isotope. Therefore recently, the isotope cobalt-56 has begun to be produced for this purpose ($T = 77.3$ days, $E_\gamma = 3.25$ (12 percent); 2.99 (2 percent); and 2.61 (16 percent) Mev).

At the present time, deuterium meters similar in design to beryllometers have been built for analyzing deuterium. To protect the detectors from gamma-rays of the source, the source is also placed along with the sample in the lead shield. /104

The design of the deuterium meter of the GeoKhI, USSR Academy of Sciences, is shown in Fig. 12.4. Twenty proportional counters containing enriched boron-10 are used in the unit. The sample

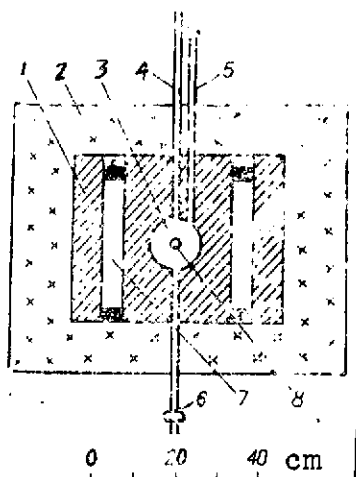


Fig. 12.4. Schematic diagram of the deuterium meter of the GeoKhI, USSR Academy of Sciences:

1. Cylindrical lead block
2. Paraffin reflector
3. Metal vessel for housing samples
- 4, 5, and 6: Outlet tubes
7. Proportional counters
8. Gamma-quanta source

volume is chosen as 0.6 liter. A source with an activity of about 100 mcurie is used for analysis in the unit. The natural neutron background of this deuterium meter is 12 pulses/min (0.6 pulses/min per counter). The background from the source, in the absence of a sample, was increased to 16 pulses/min (by the expulsion of photoneutrons from the paraffin reflector). Choice of a large-volume sample made it possible not only to obtain high yields of photoneutrons from it, but also simultaneously to use it as a moderator. This design of the device provides for recording 2.5 percent of neutrons of the total number originating in the samples. The effectiveness of deuterium meters can be enhanced by using helium counters, and also by placing between the sample and the detectors a moderator layer not containing deuterium. Deuterium-purified protium water

as well as graphite can serve as this moderator.

The deuterium content in water samples is determined with this deuterium meter at a relative error of 1.5-2.5 percent.

4. Beryllometers for Studying Rocks at Their Bedding Sites

A large number of field beryllometers with proportional boron and helium counters, as well as scintillation counters have been built in exploring for beryllium deposits, in the USSR and abroad. Since 10-50 mcurie antimony-124 sources are used in field beryllometers, the devices are carried by two persons using a pole about 2.5 m long. The Berill-3 unit carried on a one-field cart was built in the USSR for determining beryllium in bedrock. A schematic diagram of this device and its external view are shown in Figs. 12.5 and 12.6. The detector is protected against direct source radiation with a 3 mm lead layer. In order to reduce its weight, the shielding is made in hemispherical form. A 12 cm diameter of plexiglas insert simultaneously acts as a moderator and a light guide (admitting light flashes from scintillator to photomultiplier). To check the

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operation of the beryllometer, a beryllium bronze disk is placed over the second part of the lead hemisphere mounted in the cart. The presence of the paraffin moderator permits this disk to be used as a dummy standard. The beryllium content in the disk here corresponds to some specific beryllium concentration in rock -- -- estimated by comparison with the measurement of an actual rock with a known beryllium content .

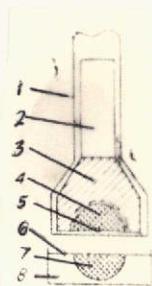


Fig. 12.5. Schematic diagram of portable beryllometer transducer:

1. Body of case
2. FEU-13 photomultiplier
3. Plexiglas insert containing phosphor
4. 3 cm thick lead shield
5. Gamma-quanta source
6. Working standard of beryllium bronze
7. Transporting lead shield
8. Paraffin

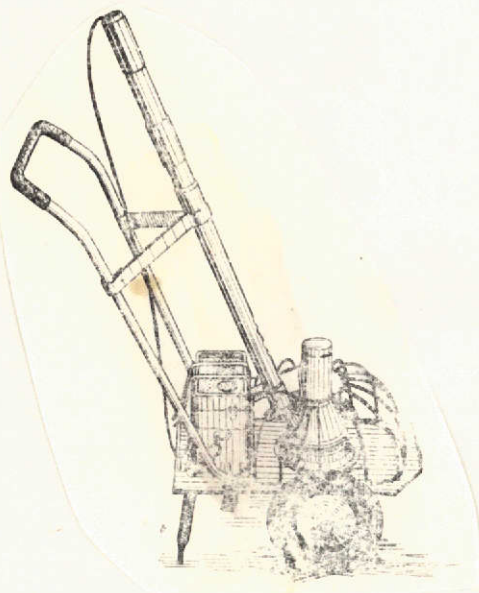


Fig. 12.6. External view of model Berill-3 beryllometer

When measurements are taken with a 5 mcurie source using this device, beryllium can be determined in rocks starting at 0.001 percent, in 15 minutes. Increased beryllium concentrations are determined in a shorter time.

The Berill-4 with a 30 mcurie source was developed for determining beryllium concentration (from $4 \cdot 10^{-4}$ percent and higher) in rocks.

Vehicular prospecting compared with ambulatory is more productive. Therefore for exploring for beryllium deposits in locations accessible to motor vehicles, the All-Union Institute of Prospecting Geophysics developed a vehicular device with a 0.5 curie source, containing 46 proportional boron counters. When the device is being conveyed at 5-6 km/hr along routes,

beryllium content in rocks from 0.003 percent and higher can be determined. Lower beryllium concentrations in rocks can be determined only when the vehicle is halted.

In the USSR, this technique began to be used in determining beryllium in rocks drilled with test holes, since 1958. At the present time this apparatus is used in field conditions. Using scintillation counter-based devices, not only can ore bodies be found, but their thickness estimated and the beryllium reserve in the deposits of this metal can be calculated. In exploratory work, beryllium content is determined starting at 0.005 percent when the rate of raising the well-logging devices 250-300 m/hr. In detailing work at speeds of 25-30 m/hr, beryllium concentration starting at 0.001 percent can be determined, and when the device is halted in motion (point measurements) -- beginning at $5 \cdot 10^{-4}$ percent. This technique revealed a large number of new beryllium deposits.

CHAPTER THIRTEEN

HEAVYWEIGHTS IN EXPLORATION

1. Heaviest Radioactive Particles

Of the radioactive particles of isotopic irradiators (see Chapter One), the heaviest are alpha-particles (nuclei of helium-4). Their mass is four units, while the charge is two units ($2e^+$). They are capable of interacting only with the upper layer of the irradiated matter about 25 microns thick. Here both scattering of alpha-particles as well as absorption by the nuclei of the atoms of the material can occur, leading to various nuclear reactions. By studying scattered alpha-particles and the secondary particles appearing in reactions, we can evaluate the composition of the material irradiated. At the present time, several alpha methods used in solving these problems have been realized.

2. Alpha-Prospectors of Earth and Space Objects

In studying the composition of matter, use is made of the phenomenon of alpha-particle scattering and several reactions with atomic nuclei.

The property of alpha-particle scattering by atomic nuclei of the matter in the radiated medium by large angles (more than 90 percent) were studied even by German scientists G. Geiger and E. Murdock in 1909. S. A. Allison (US) proposed using this phenomenon to analyze irradiated surfaces, and in 1961 the suggestion was realized in the United States by A. L. Turkevich. /107

A. L. Turkevich showed that a technique based on alpha-particle scattering can be used in determining light elements, from beryllium to iron. The dependence of the alpha-particle scattering effect for this range of chemical elements in the periodic system of D. I. Mendeleev depends on the atomic number of the elements

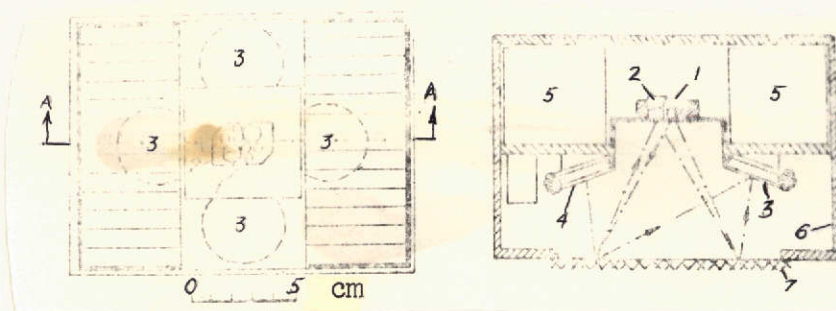


Fig. 13.1. Layout of head of device used in alpha- and proton measurements

1. Source
2. Alpha detector
3. Proton detector
4. Foil absorbing alpha-particles
5. Preamplifiers
6. Instrument housing
7. Irradiated surface

Z to the power $3/2$ ($Z^{3/2}$). In studying this effect, it was established that besides alpha-particle scattering, the reaction (α, p) by the nuclei of boron, nitrogen, fluorine, sodium, magnesium, aluminum, and silicon arise. Thus, by recording the scattered alpha-particles and protons generated in the reaction (α, p), one can determine the content of the main rock-forming elements. In realizing these techniques, the following isotopes are most advantageously used as the radioisotopic sources of alpha-particles: curium-242 ($T = 163$ days, $E_\alpha = 6.1$ Mev), curium-244 ($T = 17.4$ years, $E_\alpha = 5.8$ Mev), and plutonium-238 ($T = 86.4$ years, $E_\alpha = 5.5$ Mev), with yields to $5 \cdot 10^9$ particles/sec. Alpha-particles and protons are measured with high-resolution spectrometric semiconductor powders incorporating amplitude analyzers.

One of the devices built by A. L. Turkevich and others is shown in Fig. 13.1. The device has four alpha-particle sources, one semiconductor alpha-detector, and four semiconductor proton detectors. In order for the alpha particles not to strike the proton detectors, they are shielded with a 10 micron gold foil. This insulation proved to be highly miniaturized. Its total weight without analyzers is no more than 200-300 g.

Analysis of matter in earth conditions using this device takes place in vacuum chambers. The devices of this type are used in analyzing meteoric matter and rocks. The sensitivity threshold of the instrument to the above-indicated elements has been estimated as 0.5-1.0 percent.

TABLE 4
DATA FROM AN ANALYSIS OF ROCK FROM THE LUNAR SURFACE, WEIGHT PERCENT

| Element | Radio wave method | Sea of Tranquility | | | Ocean of Storms | | Sea of Fertility | | Sea of Rains | Crater of Apollonius | |
|----------------|-------------------|--------------------|--------------|----------|-----------------|---------|------------------|---------|--------------|----------------------|-------------|
| | | Surveyor 5 | Apollo 11 | regolith | Apollo 12 | | Luna 16 | | Luna-10 | Luna 20 | |
| | | prelim. results | rev. results | | regolith | basalts | regolith | basalts | regolith | regolith | anorthosite |
| Oxygen . . . | 41.0±4.2 | 40.1±3.5 | 43.52 | 42.11 | 41.99 | 40.94 | 41.78 | 42.14 | — | 45.07 | 44.34 |
| Sodium . . . | 2.0±0.5 | 2.0 | 0.3 | 0.4 | 0.24 | 0.26 | 0.22 | 0.20 | — | 0.41 | 0.30 |
| Magnesium . . | 2.2±0.5 | 3.2±3.2 | 2.65 | 4.8 | 7.24 | 7.05 | 5.26 | 4.25 | 7 | 5.85 | 7.25 |
| Aluminum . . . | 10.7±2.4 | 4.3±2.4 | 7.63 | 6.9 | 7.41 | 5.93 | 8.12 | 7.23 | 7 | 12.10 | 10.77 |
| Silicon . . . | 21.0±3.7 | 25.2±2.4 | 21.6 | 20.0 | 19.6 | 18.7 | 19.50 | 20.40 | 20 | 20.60 | 19.80 |
| Potassium . . | — | — | — | 0.1 | 0.16 | 0.05 | 0.08 | 0.13 | 1 | 0.08 | 0.43 |
| Calcium . . . | 10.6±2.6 | 10.4±3.5 | 10.35 | 8.6 | 7.14 | 7.63 | 8.72 | 7.44 | 8 | 10.86 | 13.30 |
| Titanium . . . | — | — | 4.56 | 4.2 | 1.86 | 2.22 | 2.03 | 2.94 | 4 | 0.34 | 0.23 |
| Chromium . . . | — | — | — | 0.25 | 0.28 | 0.38 | 0.21 | 0.19 | — | — | — |
| Manganese . . | — | — | — | 0.18 | 0.19 | 0.20 | 0.16 | 0.15 | — | — | — |
| Iron . . . | 12.3 | 12.1±4.8 | 9.4 | 12.4 | 13.25 | 16.57 | 13.05 | 15.05 | 12 | 4.0 | 4.48 |
| Total . . . | 99.8 | 97.3 | 100.01 | 98.02 | 99.13 | 99.94 | 99.14 | 100.15 | | 100.44 | 100.90 |

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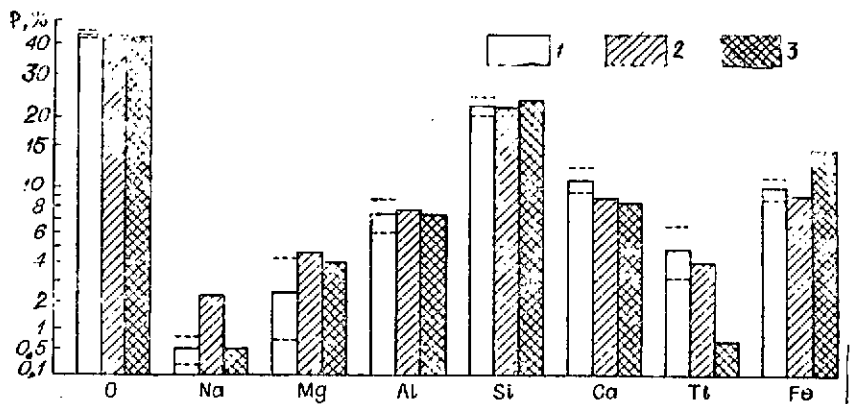


Fig. 13.2. Data from an analysis of lunar rock collected by Surveyor 5 (1) compared with data from an analysis of terrestrial oceanic basalts (2) and meteoritic material (3)

The diminutiveness of these devices caught the attention of scientists engaged in space research. And American nuclear prospectors now followed the Soviet nuclear densimeter (see Section 7, Chapter Four) to the Moon. Via spacecraft Surveyor 5, 6, and 7, they landed on the Moon in September and November, 1967, and in January, 1968. The results of analyzing lunar rock and a comparison with other data are in Table 4.

Soviet scientists also engaged in resolving this problem. Thus, V. S. Troitskiy undertook radio wave probing of the Moon in the 3-meter wavelength. His results were compared with data from similarly studying terrestrial rock and they established that there is good agreement with the indicators of direct preliminary investigations of lunar rock by nuclear methods. Later, American scientists took into account the effect of titanium on the results of the measurements and corrected their preliminary data.

From the table shown it is also clear that the Surveyor indicators agree closely with the materials of a direct analysis of lunar samples brought to earth.

Analysis of the tabulated data and the data in Fig. 13.2 shows that lunar rock differ mainly from analogous rocks of terrestrial origin by their increased content of titanium and their reduced potassium content.

3. Neutrons and Gamma Rays Ejected by Alpha-Particles

Under the effect of alpha-particles from radioisotopic sources, as already remarked in Chapter Twelve, the reaction (α, n) can be induced. It occurs mainly in the nuclei of beryllium, boron, and **fluorine**. This reaction is widely used in producing neutrons in a variety of radioisotopic sources and can be employed when determining these elements in samples by recording the neutrons formed. /110

Under the effect of alpha-particles, instantaneous gamma-radiation can be induced in the reactions $(\alpha, n\gamma)$, $(\alpha, p\gamma)$, and so on, as well as in the inelastic scattering of alpha-particles by atomic nuclei and in their coulombic excitation. The interaction of alpha-particles with the nuclei of atoms of various chemical elements leads to the generation of gamma-quanta at different energies. By recording this radiation with spectrometric detectors, one can judge the content in the media studied of several chemical elements whose atomic nuclei enters to the corresponding reaction or are excited by alpha particles.

To determine the content of several elements in samples, A. L. Yakubovich et al. (USSR) built an integrated device containing neutron and gamma-spectrometric detectors. With this unit, the content of beryllium, boron, and fluorine is determined in samples with a sensitivity threshold of 0.02, 0.04, and 0.15 percent, respectively.

Various radioactive isotopes can also be formed in the reactions (α, p) , (α, n) , and others. By measuring their induced radioactivity, one can judge the content of several elements (boron, aluminum, and so on) in samples.

However, in conclusion we note that the alpha-techniques examined in this section are not widely employed. This is due mainly to the weak penetrating ability of alpha-particles in matter. Test samples must be carefully ground and dried, however the change in mineralogical composition shows up in the measurements. All this then limits the scope of these techniques in nuclear analysis.

CHAPTER FOURTEEN

HOW OLD IS THE EARTH, MOON, AND MAN?

1. How is the Age of Earth and Other Objects Determined?

Man has long been interested in the problem of determining the age of rocks and of the earth as a whole. Answering this question proved possible only after the discovery of radioactivity. We know that the decay of radioactive nuclei occurs at a constant rate that is independent of the change in the surrounding physicochemical condition.

The decay of a number of isotopes -- uranium, thorium, /111
potassium-40, and others -- is studied in determining the age of natural formations. In these investigations it is important to determine the initial (n_0) and final (n) content of the radioactive isotope in natural formations. Knowing them, it is not difficult also to determine the age of the objects studied. One can judge the initial content of the radioactive isotope in the object studied from the quantity of stable product formed n_c . The final content of the radioactive isotope in the object studied is determined using radiometric, radiochemical, and other techniques. These initial and end products are associated by the following relationship:

$$n_0 = n + n_c \quad (1)$$

The decay of radioactive nuclei obeys the following exponential law:

$$n = n_0 e^{-\lambda t} \quad (2)$$

where $\lambda = 0.693/T$ is the decay constant and T is the half-life. Both these quantities are known precisely.

By inserting Eq. (2) into Eq. (1) and performing several manipulations, we get

$$n_c = n(e^{\lambda t} - 1) \quad | \quad (3)$$

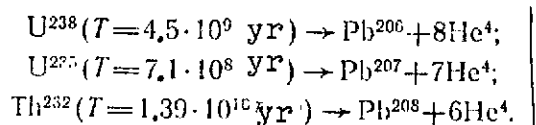
or

$$\frac{n_c}{n} + 1 = e^{\lambda t}. \quad | \quad (4)$$

Taking the logarithm of this expression, we can write

$$t = \frac{2.3}{\lambda} \lg (1 + n_c/n). \quad | \quad (5)$$

Initially, techniques based on the decay of uranium, actino-uranium, and thorium were first used to determine the age of rocks:



As we can see, lead or helium isotopes can be used as the final products. These methods came to be called lead and helium techniques, respectively.

The decay of potassium-40 ($T = 1.25 \cdot 10^9$ years) led to the formation in one chain of calcium-40, and argon-40 in another. Techniques based on these end decay products came to be called the potassium-calcium and potassium-argon methods, respectively.

In nature we also encounter the isotope of radioactive rubidium -- rubidium-87 ($T = 5.25 \cdot 10^{10}$ years), whose decay forms strontium-87. The method based on a determination with these isotopes is called the rubidium-strontium method.

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Still other techniques are employed in determining the age of geological formations. Thus, to determine young geological formations use is made of a technique based on the decay of radiocarbon -- carbon-14 ($T = 5685$ years). Its end decay product is nitrogen-14. In the literature, this method is called the radiocarbon method. It is used not only in geology, but also archaeology.

With these techniques, the age of rocks can be determined in limits of about 10 half-life periods from the moment of formation of the closed system, that is, it is important that the parent isotopes and the decay products did not migrate from the object studied.

2. Age of Earth, Moon, and Other Space Objects

In accordance with calculations by the above-presented techniques, the earth's age is estimated at 4.6 ± 0.1 billion years. However, this value refers to the age of the earth's existence already with formed shells (core and others). The true age of the earth as a separately formed planet is estimated as 4.7-5 billion years.

The most ancient of the earth's rocks, granites and shale bedded in the Antarctic (Enderby Land) are 4 billion years old. Rocks from the Okhotskiy Massif (USSR) and Western Greenland are 3.9 billion years in age. Gneisses aged 3.55 billion years have been discovered in the state of Minnesota (US). The oldest rocks corresponding to the above-indicated age of 4.6 billion years have yet to be found.

From samples brought to the earth from the moon from the Sea of Tranquility (Apollo 11), Ocean of Storms (Apollo 12), and the Sea of Fertility (Luna 16), it was established that their age is similar in absolute values and can be taken as 4.5 billion years. The determination of the age of Martian rock is scheduled for the late 1980's, after their samples will be taken from this planet's surface back to the earth.

The age of stony meteorites collected by scientists on earth is also estimated at 4.5 billion years.

Thus, the age of the earth, Moon, and meteorites is determined by values that are similar. This affords grounds for assuming that the age of the entire solar system is 4.7-5 billion years. The age of our galaxy has been estimated at 10 billion years.

Based on a study of the age of benthic deposits of oceans, seas, lakes, rivers, and so on, scientists have concluded that present-day oceans were formed 150 million years ago.

3. Time of the Emergence of Life and the Appearance of Man on Earth /113

A number of specific reactions of the formation of amino acids, nitrogen compounds, sugars, porphyrins, and so on occurred on earth owing to solar radiation, the heat of the earth, and other factors. From the simplest compounds there were later formed more complicated biological molecules, precursors of modern proteins and nucleic acids. On their basis there subsequently emerged the simplest living structures capable of self-reproduction. This stage of chemical evolution lasted 1-1.5 billion years.

TABLE 5
STAGES IN EVOLUTION OF PRIMATES AND MAN

| Stages of Evolution | Time of appearance, millions of yrs ago | Stages of Evolution | Time of appearance, thousands of yrs ago |
|---|---|---|--|
| Pliopithecus -- early protohominid ape, resembling modern gibbon | 37 | Australopithecus robustus -- used primitive implements (stones with several chipped areas) | 2000 |
| Proconsulus -- early anthropoid ape, ancestor of chimpanzee | 26 | Homo erectus -- first "true" man, using fire and knives | 1000 |
| Driopithecus -- first fossil hominid ape | 20 | Early man -- most developed representative of modern man, used well-developed implements, lived in Europe | 250 |
| Ramanapithecus -- most ancient ancestor of man along line of direct descent | 14 | Neanderthal -- used stone implements and lived in Europe and in the Middle and Near East | 150 |
| Australopithecus africanus -- first man moving in upright posture | 5-3 | Cromagnon man -- differed only slightly from modern man, lived in Europe, Africa, and China | 40 |

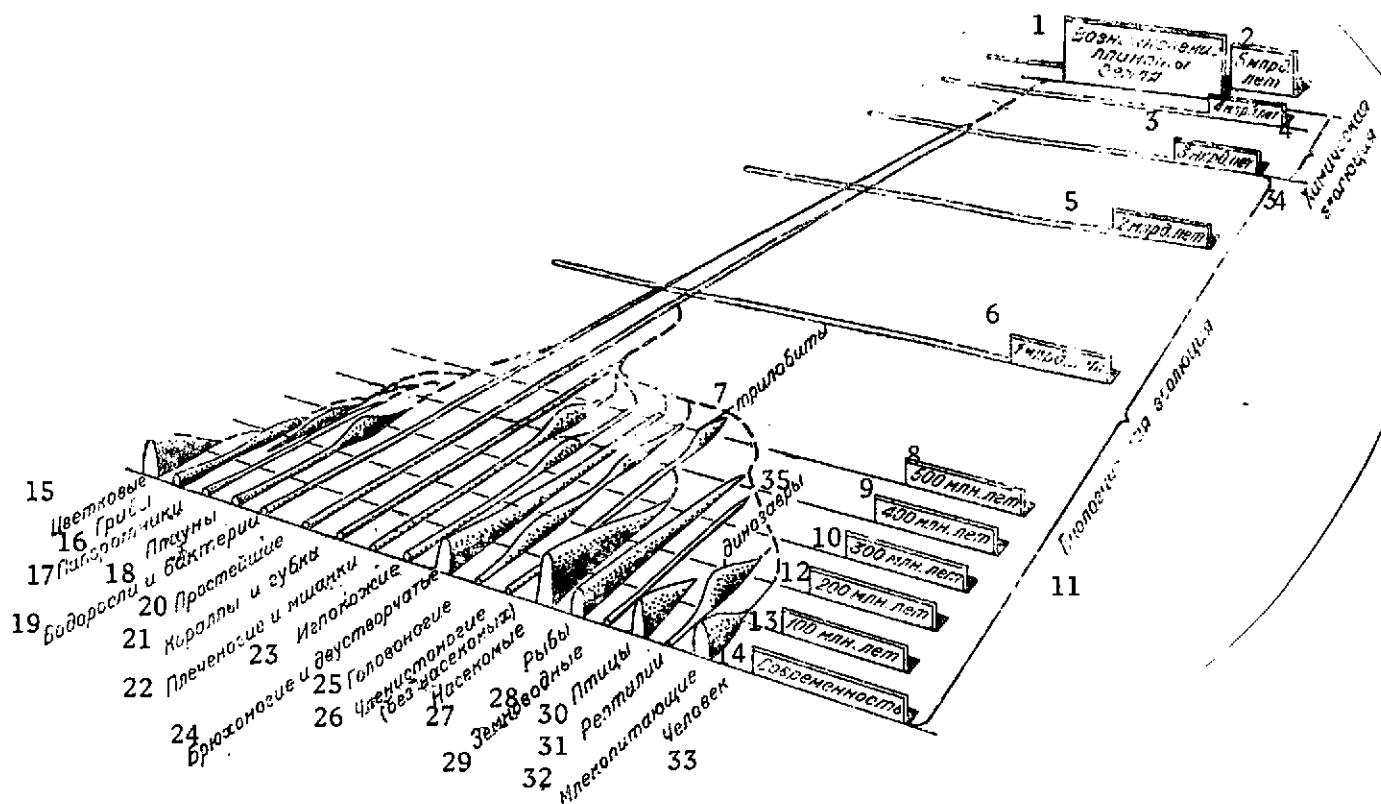


Fig. 14.1. Stages in evolution of life on earth*

See Nauka i zhizn', No. 8, 1973, p. 63

KEY:

- | | |
|------------------------------|------------------------------------|
| 1. Emergence of planet earth | 19. Algae and bacteria |
| 2. 5 billion years | 20. Protozoa |
| 3. 3 billion years | 21. Corals and sponges |
| 4. 4 billion years | 22. Brachyopods and bryozoa |
| 5. 2 billion years | 23. Echinoderms |
| 6. 1 billion years | 24. Mollusks and bivalves |
| 7. Trilobites | 25. Cephalopods |
| 8. 500 million years | 26. Arthropods (excluding insects) |
| 9. 400 million years | 27. Insects |
| 10. 300 million years | 28. Fishes |
| 11. Biological evolution | 29. Amphibians |
| 12. 200 million years | 30. Birds |
| 13. 100 million years | 31. Reptiles |
| 14. Present day | 32. Mammals |
| 15. Flowering plants | 33. Man |
| 16. Fungi | 34. Chemical evolution |
| 17. Ferns | 35. Dinosaurs |
| 18. Mosses | |

After the chemical there began the biological, Darwinian evolution, emerging about 3-3.5 billion years ago. This is confirmed by individual finds of the most ancient of microorganisms in rocks whose age has been determined by products of radioactive decay. Thus, impressions of primitive aquatic plants found in minerals of South and Central Asia and, in particular, the Sahara, have been dated at 2.7 billion years. Microorganisms similar to present-day blue-green algae, detected in the iron-bearing formation Gunflint in the area of Lake Ontario (US) are 1.9 billion years old. Aquatic algae and fungi detected in clayey shale of Nonesuch in the area of Lake Superior (US) are 1.05 billion years old. /115

These organisms precede the flora (vegetation) and fauna (animals). In particular, this can be judged from the data of the diagram shown in Fig. 14.1. From it we see that the most intense developed of flora and fauna began about 600 million years ago. Man appeared on earth roughly 40 million years ago. The stages in the evolution of primates and man can be judged from the data of Table 5. The earliest remains of man's ancient ancestor are discovered in deposits 15 million years old. Bone remains found in rock are mineralized so that their age can be determined directly from the content of radioactive products in the bone mineral formations.

CHAPTER FIFTEEN

LABELED ATOMS

1. What are Labels?

The use of labels in scientific research has a long history. Ornithologists label (band) birds to follow their migrations. Ichthyologists label fish by attaching numbered tags to their fins. Zoologists label (stamp or secure tags to ears, and so on) large wild animals to keep track of their migrations. Semiconductor equipment in animal labeling has wrought a major revolution. Miniature transmitters powered by the heat given off by the body have begun to be used as labels. Thus, aquatic swimming animals (whales, seals, and so on) are labeled and their movements are followed by radio triangulation.

Scientists have long been fascinated by the idea of devising labels to keep track of the movement of individual atoms and their compounds in the living organism and in plants. These problems were capable of solution only due to the appearance of radioactive isotopes that reveal themselves by emitting radioactive particles. By adding these labeled compounds to various substances, it was possible to follow the path of the substances in plants and in animal organisms. Chemists also used these labels in studying diffusion, dissociation, absorption, desorption, and so on.

2. Labeled Atoms in Geology

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In geology sometimes it becomes necessary to study the movement of groundwater in strata hidden from the observer, and so on. By adding labeled compounds to portions of water, these problems can also be solved. Radioactive isotopes came to be used as labeled atoms. In addition, it was found that other compounds whose atomic nuclei have anomalous properties with respect to the radiation acting on them, and so on, could be

used in solving a number of problems. For example, Chapter Ten told about the existence of neutron absorbers. By adding these neutron absorbers to substances, it was possible to follow their movement in various media by the use of nuclear techniques.

The labeled substance is usually pumped into the stratum under study in one well -- the startup well, and its appearance is recorded in others -- control wells, which are drilled at some distance around the startup well.

The study of groundwater hydrodynamics is based on this principle, for example, when exploiting minerals by the shaft method. In mining work it often is the case that water begins to enter a shaft from several horizons. Labeled compounds are also used to find the location of water inflow. After the flooding site has been discovered, appropriate measures are taken by acting on the site and changing the direction of flow of the water from it. Labeled compounds again serve control functions.

Groundwater hydrodynamics is also studied in the operation of oil deposits, with the so-called externally contoured or internally contoured flooding of strata. Essentially this method of intensifying petroleum recovery amounts to the following. Wells are drilled around the contour of the petroleum deposit or within the contour, then water is pumped into them under pressure. Here it is important that the water into the strata underlying the petroleum deposit. The arriving water acts on the petroleum strata and assists in more intensively extracting the petroleum from it. Labeled compounds also monitor this process.

These kinds of problems also confront geologists searching for sections in which to build various structures. Before designing the structures it is important to study precisely the geology and hydrogeology of the locale. Labeled compounds are also resorted to in studying the direction of groundwater flows. A similar kind of problem arises also in monitoring dams and other structures during their operation.

As already noted, radioactive compounds easily soluble in water usually serve as the labeled compounds in studying all the above-listed problems in the initial stage of research. Salts of sodium or potassium iodide labeled with iodine-131 ($T = 8.06$ days) were used as these compounds. This isotope is an intense gamma-irradiator. Its appearance in control wells is easily recorded with well-logging gamma-radiometers.

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Subsequently, in order not to contaminate water with radioactive compounds, nonradioactive substances came to be used as the labeled compounds. Thus, to portions of ordinary water heavy (deuterium) water is added. In chemical properties they show no

difference from ordinary water but still can easily flow through porous rock. Water is regularly sampled at the required depth in control wells. The determination of the heavy water content in the control well is made with deuterium meters (see Section 3, Chapter Twelve).

When solving some geological problems, it is important to keep track of the incursion of liquid from the well shaft into individual strata. To solve this problem, in contrast, one must use labeled compounds that are easily absorbed in rock at the point at which liquid enters. Initially radioactive compounds were used, but recently compounds containing boron and cadmium began to be used. The points of accumulation in a well of these compounds are easily determined by using well-logging instruments equipped with a neutron source. Compounds of fluorine easily activated when exposed to fast neutrons are also used as the labeled compound.

This kind of technique is used most widely in oil-field geology. To increase the oil yield of productive strata in operating wells and the response of strata in pressure wells (with external contoured or internal contoured flooding), oil men began to use the so-called method of hydraulic discontinuity, which is based on the rupture (stratification) of a stratum when it is treated with a viscous liquid pumped in at high pressure. Together with the liquid, coarse sand is pressured into the strata being ruptured in order to retain the air cracks after the pressure in the well is turned off. Labeled compounds are also added to the sand for monitoring of this process.

Using a similar technique with labeled compounds, the technical condition of the casing column in oil wells, and so on, is kept track of.

CHAPTER SIXTEEN

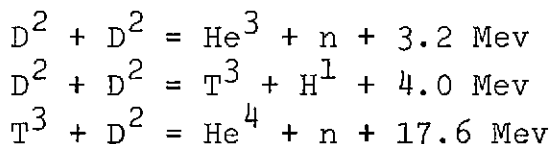
LIGHT ARTILLERY IN POSITION

1. Peaceful Use of Nuclear Synthesis

The formation from some light nuclei of other -- heavier -- nuclei is called nuclear synthesis. The highest energy is released in the synthesis of the lightest nuclei -- hydrogen isotopes: protium -- H^1 , deuterium -- H^2 or D^2 , and tritium -- H^3 or T^3 . The synthesis of these nuclei in various combinations leads to the formation of helium nuclei -- He^3 or He^4 with the release of tremendous energy.

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Ordinarily the following synthesis reactions are used in achieving the hydrogen bomb:



As we can see, the greatest amount of energy is released in the last reaction, and moreover it occurs for lower deuteron energies than the first two.

For these reactions to occur, the atomic nuclei must be driven to high energies in order to overcome the coulombic forces of nuclear repulsion. In the hydrogen bomb the required high energies are imparted to the hydrogen nuclei in an atomic explosion based on the fission of nuclei of uranium, plutonium, and so on.

Since in some of the reactions we are considering neutrons (n) are released, physicists used these phenomena to obtain powerful controlled neutron sources. The high energies are imparted to the hydrogen nuclei (to the deuterons -- d) with high-voltage sources.

To obtain neutrons by the principle examined here, special neutron tubes were developed, used in science and technology in solving various peaceful problems. The schematic layout of these tubes can be seen from the schemes in Figs. 16.1 and 16.2.

Gas-filled tubes operate at a deuterium pressure of 10^{-3} - 10^{-4} mm Hg. Electrons wrenched from the incandescent tungsten spiral ionize the deuterium. Acted on by the applied difference of the potentials between the ion source cathode and anode, they are accelerated along the tube axis and enter the accelerating gap of the tube with focusing diaphragm. Under the effect of the applied potential difference of about 100,000 volts, the ions like artillery shells bombard a tritium target. A specific vacuum is maintained in the accelerating gap of the tubes in order to avoid the collision of deuterium ions with gas atoms.

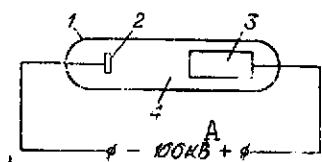


Fig. 16.1. Schematic of neutron tube

1. Glass cylinder
2. Tritium target
3. Source of deuterium ions
4. Gap in which ions are accelerated

KEY: A. 100 kv

Neutron tubes built in the Soviet Union are highly miniaturized (from 20 to 76 mm in diameter and 155 to 210 mm in length). With them, neutron fluxes up to 10^8 - 10^9 neutrons/sec can be achieved. At the present time tubes are being produced with yields

up to 10^{10} neutrons/sec. Since the synthesis reaction occurs in the surface layer of the target, acted on by deuterons the tritium relatively rapidly "burns up." The first neutron tubes were designed for 10-20 hours of continuous operation. At the present time tubes are being produced on a mass basis with service life of 100 or even 1000 hours. The longevity

of some of the tubes is achieved by tritium make-up. Present in the ion source along with deuterium is also tritium. Ions of these isotopes are accelerated and bombard the target. As this happens, tritium is driven into the target, which permits extending its service life.

Neutron tubes can be operated in the continuous (stationary) or pulsed regimes. The pulsed regime is the more effective. Moreover, a large number of new neutron methods can be realized, which we will show below.

2. Expiring Neutrons Help Geophysicists

Geophysicists developing new nuclear methods for solving diverse geological problems were attracted earlier than others by the miniature neutron tubes and on their basis built neutron

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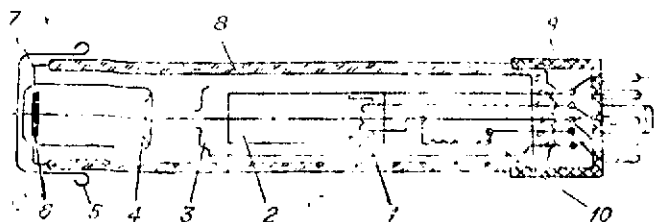


Fig. 16.2. Scheme of universal neutron gas-filled tube (UNG-1):

1. Incandescent tungsten cathode
2. Anode of ion source
3. Focusing diaphragm
4. High-voltage electrode
5. Shielding foot
6. Titanium-tritium target
7. High-voltage lead of target
8. Glass cylinder
9. Base
10. Inleakage device (deuterium storage)

generators for investigating test wells. Academician G. N. Flerov proposed in 1956 using the pulsed regime of tube operation in geophysics for developing new pulsed neutron sources. The realization of pulsed methods showed their advantage compared to old neutron methods based on isotopic sources continuously emitting neutrons.

In order to find the essentials of pulsed neutron methods, let us examine the scheme shown in Fig. 16.3. The tube emits neutrons over a short period of time -- of the order of several microseconds ($\Delta T = n \cdot 10^{-6}$ sec). The pulse repetition frequency rate is chosen in

the range of several Hertz to 400 Hertz. Some tubes operate at the commercial frequency -- 50 Hertz.

When tritium is bombarded with deuterons, fast 14 Mev neutrons are emitted. On entering the well filled with liquid and on entering rocks, the neutrons experience collisions with atomic nuclei (mainly with hydrogen) and reduce their energy down to the thermal state of matter. The process of neutrons slowing down to thermal energy occurs usually in several microseconds, that is, commensurable with the time during which one pulse of fast neutrons acts. But thermal neutrons in an irradiated medium as a rule live for a longer time. Thus, the mean lifetime of thermal neutrons in water is $2.1 \cdot 10^{-4}$ sec. For dry sandstone, the mean lifetime of thermal neutrons is $1.3 \cdot 10^{-3}$ sec. The presence of moisture in its pores in amounts of 20 and 35 percent leads to a decrease in this time down to $6.5 \cdot 10^{-4}$ and $4.6 \cdot 10^{-4}$ sec, respectively, and so on.

Thus, if in a well the rocks are irradiated with a neutron flux, in the shaft of the well they die out much faster than in the rocks. This phenomenon was used by geophysicists to eliminate the effect of well liquid on the results of determining neutron parameters of rocks. It proved possible to solve this problem only with the pulsed operating regime of the well-logging neutron generator.

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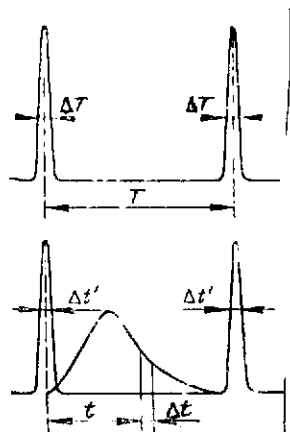


Fig. 16.3. Irradiation and measurement scheme for pulsed neutron methods:

- ΔT = duration of pulses at half-height
- T. Time between neutron pulses
- $\Delta t'$ = duration of pulsed ring in which gamma-radiation of the inelastic neutron scattering is studied
- t. Delay time after pulse determination
- Δt = time interval during which distribution in well of thermal neutrons or their captured gamma-radiation is studied

From Fig. 16.3 we see that after a pulse of fast neutrons, the rise in the flux of thermal neutrons with time occurs up to a certain value (maximum), and then begins to decline. Therefore it is advantageous to begin recording thermal neutrons after a pulse not at once, but after some time interval, called the delay (t). Neutrons or the gamma-rays they generate in the reaction (n, γ) are recorded during some time Δt , called the time window of the device. Depending on the problem solved, the delay time and the time for recording neutrons or gamma-rays are chosen as different values. The delay is advantageously selected so that neutrons on propagating through the well shaft die out. After some time, neutrons enter the well from the rocks. These neutrons bear information about the rock and are recorded during the time Δt . In plots of neutron well-logging, rocks of different material composition stand out by the different values of the neutron flux recorded, which in fact is used by geophysicists in solving several geological problems in well studies.

Pulsed neutron methods based on measuring fluxes of neutrons and gamma rays as applied to studying well profiles came to be called pulsed neutron-neutron well-logging (PNNWL) and pulsed neutron gamma-well logging (PNGWL), respectively. Both methods began to be resorted to first in the

striking through the water-petroleum contact in the event that the water-bearing stratum contained mineralized water with sodium chloride. The intense absorption by chlorine of neutrons leads to an abrupt drop in the rate at which neutrons and gamma-rays were recorded as compared to these strata with a well casing. By the PNNWL technique, the water-petroleum contact is broken through when the water is mineralized from 30-50 g/liter and higher, and according to the PNGWL technique -- from 10-15 g/l and higher. Both methods are resorted to, in a study of these collectors, to determine the porosity of rocks and their saturation.

The techniques of PNNWL and PNGWL can be used to determine the presence in wells of lithium, boron, manganese, iron, cadmium, rare-earth elements, and mercury. The PNGWL technique is also used to establish the presence in rocks of titanium, chromium, nickel, copper, and other elements of vital national-economic significance.

Acted on by fast neutrons, gamma-radiation can be generated in the reaction $(n, n'\gamma)$. This radiation exists only during a pulse, therefore in taking measurements of different time lengths, it is completely distinct from the gamma-radiation arising in the reaction (n, γ) under the effect of thermal neutrons. The reaction $(n, n'\gamma)$ can be used above all in solving problems associated with determining oxygen and carbon in rocks.

Well-logging equipment involving neutron generators is used also in studying the elemental composition of rocks by the method of neutron activation analysis. This method is suitable above all for estimating the content of oxygen, silicon, aluminum, fluorine, and other chemical elements.

3. Neutron Combine for the Study of Earth and Space Objects

Based on neutron tubes, devices can be designed for integrated investigations of rocks simultaneously by several techniques. This equipment can be located on a truck trailer. The device gives the characteristic of moisture in rock, their density, and their chemical composition.

A device carried in a truck trailer has been built in the United States for measurements based on the neutron activation method. The device successfully records the silver concentration in ore in the amount of 0.004 percent.

R. L. Caldwell et al. (US) developed the plans for a neutron instrument for integrated investigations (combines) of the surface of celestial bodies. The design of the device is shown in Fig. 16.4. Radiation from the target strikes the rock. With gamma-ray and neutron detectors, information is obtained simultaneously on the density of rocks and their content of hydrogen, and from the gamma-radiation induced in the reactions $(n, n'\gamma)$ and (n, γ) , one can judge the content in the rocks of the primary rock-forming elements. While the content in rocks of chemical elements in a layer several microns thick (see Section 1, Chapter Thirteen) could be evaluated by means of Surveyor 5, 6, and 7, and by using the RIFMA device (see Section 3, Chapter Seven) -- in a 2-3 mm layer, using the pulsed neutron methods a rock layer up to 1 m in thickness can be evaluated. This is a major advantage of neutron methods compared with other nuclear methods. /122

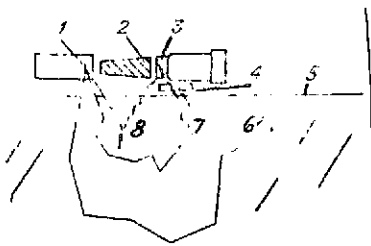


Fig. 16.4. Layout of neutron combine:

1. Target of neutral generator
2. Shield
3. Gamma-ray detector
4. Thermal neutron detector
5. Irradiated surface of rock
6. Trajectory of neutron arriving at detector
7. Gamma-radiation of neutron radiative capture
8. Gamma-radiation of inelastic neutron scattering

The equipment built has been tested in earth conditions. As a result, it was established that using the combine in recording gamma-radiation produced in the reaction $(n, n'\gamma)$, a long series of elements can be analyzed with the following sensitivity thresholds: 2.7 percent for oxygen, 1.3 percent for nitrogen, 0.3 percent for magnesium, 2.4 percent for aluminum, 0.6 percent for silicon, 1.7 percent for potassium, 2.1 percent for calcium, and 0.2 percent for iron.

Before the neutron generator is turned on, the detectors provided in it could be used in studying the natural radioactivity of rocks. Under the action of neutron generators, a large number of elements contained in the rock will become activated. This property of nuclei can also be employed when studying rocks at the apparatus landing site.

This combine can be fitted entirely in self-propelled apparatus of the Lunokhod type landed on the Moon via space stations. Here the study of rock is carried out as the self-propelled apparatus is in motion along prescribed routes.

CHAPTER SEVENTEEN

HEAVY ARTILLERY MOVES INTO POSITION

1. Heavy Artillery of Nuclear Physics

Beginning in the 1930's, in studying the properties of atomic nuclei physicists began building a variety of powerful nuclear weapons capable of driving charged particles to extremely high energies and bombarding substances with them. In 40 years this unusual physics "artillery" has traveled the road from desk type and primitive accelerator to gigantic installation. Nonetheless, even at present the need for designing miniature desk-type accelerators has not disappeared. However, whereas in the first stage of designing accelerators they were used mainly in physics research, at the present time exceptionally enormous machines are used for these purposes, while miniature accelerators are employed in varied tasks of applied importance. Examples of these have been given in the previous chapter. In it, in particular, we talked about miniature artillery weapons -- neutron tubes. /123

Increasing the energy of charged particles in an accelerator occurs in a special accelerating device through the interaction of the electromagnetic field with the particle charged. By charged particle trajectories, accelerators are subdivided into two main classes: linear and cyclic. In the first (in particular, in neutron tubes) the particle trajectory is near-linear and sometimes these are called direct-action accelerators, while in the second the particle trajectory is near-circular or spiral. In linear accelerators the particle arrives at the accelerating device once, while in cyclic accelerators -- many times. In addition, typical of cyclic accelerators is the provision of a magnet providing stable cyclic motion of the particle in the accelerator chamber. From the nature of the accelerating electrical field, each of these types of devices in turn is divided into accelerators with constant and variable fields. By this principle,

linear accelerators are subdivided into electrostatic (with constant accelerating voltage) and pulsed (with variable acceleration field). Cyclic accelerators are subdivided into the following kinds: with variable magnetic field (betatron), with constant magnetic and variable electrical fields (microtron, cyclotron), and with variable magnetic and electrical fields (synchrotron, synchrophasotron).

Of these devices, in nuclear geophysics various linear accelerators, betatrons, and microtrons are used, and cyclotrons have begun to be employed.

Using these devices, investigations are waged over a broad front in devising techniques for the nuclear analysis of matter. Note that these weapons, like those examined above (Sections 3 and 4, Chapter Three), are conveniently used in practice only if with their aid some qualitatively new results can be obtained: high precision, low sensitivity threshold, rapid return of results, and so on, that could not be realized by working with radioisotopic sources. In addition, these devices are conveniently used in analyzing elements and their isotopes that cannot be determined by simpler procedures and techniques.

Below we dwell on devices widely used in nuclear-physics analysis of samples of geological objects.

2. Neutron Devices and Their Use in Nuclear Analysis

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In Sections 3 and 4 of Chapter Three we already talked about powerful neutron installations -- neutron multipliers and nuclear reactors, whose irradiation is used in neutron activation analysis of samples of geological objects. Different kinds of neutron analysis using miniature neutron tubes was treated in Chapter Sixteen. In this particular section we will discuss the layout of powerful neutron generators and their application in neutron analysis of samples of geological objects.

To produce powerful neutron fluxes, use is made of a variety of charged particle accelerators: accelerators of electrons, protons, deuterons, and so on. Most widely used are deuteron accelerators, in which the neutrons are produced in the reaction $H^3(d, n)He^4$. In these installations, the deuterons are ordinarily accelerated to 80-100 kev, but up to 160-200 kev in the most powerful models. Using these installations, neutron fluxes up to 10^{10} , and less often up to 10^{12} neutrons/sec can be achieved. These yields correspond roughly to flux densities of $10^8 - 10^{10}$ neutrons/cm².sec.

Generally direct-action installations as the accelerators, where the high voltages are produced by using electrostatic Van de Graaff or Joffe generators and Cockcroft Walton cascade generators.

Underlying the operation of electrostatic generators is the principle of the electrophoretic machine -- a friction machine. In Van de Graaff generators, the charge on the high-voltage electrode is transferred via an endless belt, while in the Joffe rotor generators -- via a rotor driven by an electric motor. The Cockcroft Walton cascade generators consist of chains of capacitors and rectifiers (kenotrons, thyratrons, or discharge tube rectifiers), and when these are switched from series to parallel connection, the voltage is multiplied.

A special laboratory housing NG-160 neutron generators was built to analyze geological samples (Fig. 17.1 a). The high voltages up to 160 kv and currents up to 0.8 mA in this installation are generated with an electrostatic rotor generator. The neutron generator can operate in the continuous or pulsed regimes. With it one can achieve fast neutron flux densities up to 10^8 neutrons/cm \cdot sec, and thermal neutron flux densities in moderators of up to 10^6 neutrons/cm \cdot sec. The supply of samples for irradiation and to the measuring unit is achieved with a rabbit.

Recently, a more compact neutron generator of the NG-150 type (Fig. 17.1 b)) was developed for neutron analysis of samples; moreover it is capable of achieving an order of magnitude higher steady-state neutron flux densities. The high voltage in this unit is achieved with a high-voltage transformer and rectifier. In it, the ions are accelerated to 150 kev at a current of 3 mA.

To produce neutrons, we can use the reaction (d, n) with beryllium $\text{Be}^9(d, n)\text{B}^{10}$, which has a threshold of 350 kev. At a 2 Mev deuteron energy, 6 Mev neutrons can be produced via this reaction. In addition, in producing neutrons use is also made of the reactions formed under the effect of protons $\text{H}^3(p, n)\text{He}^3$, $\text{Li}^7(p, n)\text{Be}^7$, and so on. However, compared with the reactions mentioned above, these reactions are of greater energy. The threshold of the first of them is 1.019 Mev, and the second -- -- 1.882 Mev. Therefore they are used relatively rarely in generating neutrons. Both direct-action installations as well as cyclic types (cyclotron, see Section 4 of this chapter) can be used here as proton and deuteron accelerators.

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Direct-action and cyclic electron accelerators (betatrons and microtrons, see previous section) can be used to produce powerful neutron fluxes. The Van de Graaff, Cockcroft-Walton, and other generators are used as the high voltage units in direct-action accelerators.

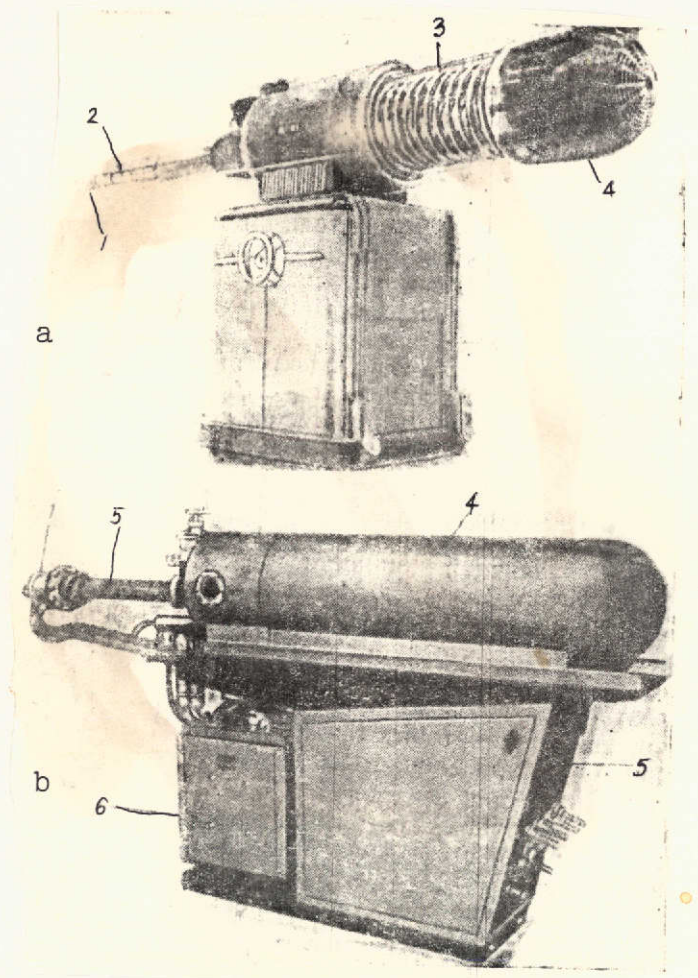


Fig. 17.1. General view of NG-160 (a) and NG-150I (b) neutron generators:

- a: 1. Target unit with water cooling
 2. Ion conductor
 3. Accelerating system
 4. High voltage electrode
 5. Power blocks and vacuum pump
- b: 1. Target unit
 2. Water cooling system
 3. Ion conductor
 4. Body of accelerating system
 5. Power block
 6. Forevacuum station

In these installations, the neutrons are produced by the interaction of bremsstrahlung gamma-radiation with beryllium or uranium. For this purpose, the target slowing down the electrons is surrounded with a block of metallic beryllium or uranium. Depending on the intensity of the radiation flux with energy above

the photoneutron reaction threshold for these elements, and the beryllium block configuration and size, continuous or pulsed fluxes of neutrons of different intensities are obtained. Thus, using a linear 30 Mev electron accelerator in the reaction (γ, n) with uranium-235, a neutron source with a mean energy of 0.8 Mev was achieved, with a yield of $3 \cdot 10^{17}$ neutrons/sec, which will correspond roughly to a fast neutron flux density of $3 \cdot 10^{15}$ neutrons/cm²·sec. However, these neutron fluxes are accompanied by intense beams of gamma rays, and various radioactive isotopes can be activated under the effect of these beams.

Accordingly, in neutron activation analysis the general practice is to use neutron generators based on the reaction $H^3(d, n)He^4$ with the chemical elements activated by fast neutrons ($E_n = 14$ Mev). When these neutrons strike light nuclei, usually the reactions (n, p) and (n, α) predominate, and when they strike heavy elements ($Z > 50$), the reaction ($n, 2n$) predominates.

At the present time more than 30 chemical elements with sensitivity threshold from several percent to $1 \cdot 10^{-4}$ percent are undergoing determination using the neutron generator. In complex samples, simultaneously copper, silicon, and aluminum can be determined with sensitivity thresholds of 0.05, 0.5, and 1 percent. This technique is involved in the simultaneous determination in samples of rare-earth elements, and so on.

Neutron generators can also be used for activating chemical elements with thermal neutrons. For this purpose, a moderating substance (paraffin, water, plastic, and so on) must be placed around the target emitting neutrons. Usually the moderator is made in the form of a separate block with a channel for accelerator and samples. This block is positioned on a sliding platform that enables the moderator block to be rolled right up to the accelerator so that its target is located within this moderator. /127 In the event that a beam of fast neutrons is being used, the platform must be provided with a means of rapidly rolling the block away from the accelerator to the required distance.

The moderators are usually made in the form of a block with about 1 meter on a side. An adequate layer of moderator must be placed between the target and the sample when placing samples for activation. The samples are brought up for irradiation and measurement usually with a rabbit.

Flux densities roughly from $6 \cdot 10^6$ to $2 \cdot 10^8$ neutrons/cm²·sec are achieved in the thermal neutron channels, depending on the primary beam of fast neutrons. These flux densities exceed roughly by 600-20,000 times the fluxes in moderators with ordinary ampoule neutron sources. Therefore, the use of neutron

generators when activating elements even with thermal neutrons can lead to a considerable rise in analytical capacity, as well as to higher precision of analysis and reduced sensitivity threshold. Thus, by working with a flux of thermal neutrons with a density of 10^8 neutrons/cm²·sec, one can determine 27 chemical elements with a sensitivity threshold similar to the value achieved when activating elements with fast neutrons.

3. Betatrons and Microtrons and Their Use in Nuclear Analysis

Cyclic electron accelerators -- betatron and microtron -- are used primarily to produce beams of bremsstrahlung x-ray radiation.

The first betatron model was built by Kerst in 1940 in the United States. With it, electrons can be accelerated to the energies of beta-particles from radioactive isotopes and higher, owing to which the accelerator came to be called a betatron.

By operating principle, the betatron resembles a transformer. As we know, in a transformer alternating current flowing in the primary winding produces in the core a variable magnetic flux, which causes an eddy electric field to appear, and thereupon also alternating current in the field winding. In the betatron, the role of the field winding is played by the electron beam (Fig. 17.2) formed in a vacuum chamber made in the form of hollow torus. This chamber is located in the annular inner gap of the electromagnet.

The force lines of the eddy electric field are closed around the cylindrical, variable magnetic flux. The electromotive force of the eddy field acts on an electron produced perpendicularly to the variable magnetic field, increasing the electron energy. In a single rotation the electron acquires energy equal to the product of its charge by the EMF of the induction in the secondary coil of the winding. In traveling, the electron accumulates more energy, the greater the number of revolutions it performs. To achieve a convenient and inexpensive magnet design, it is necessary that the particle travel roughly along a constant orbit. This condition of electron orbit stability is satisfied if at each instant of time the magnetic field strength at the orbit will be half the mean strength of the magnetic field of the entire area encompassed by this orbit. In practice, this is achieved by using specially shaped magnet pole tips (Fig. 17.2 b), which produce in the central area an accelerating field that is twice as high as the field in the electron orbit. /128

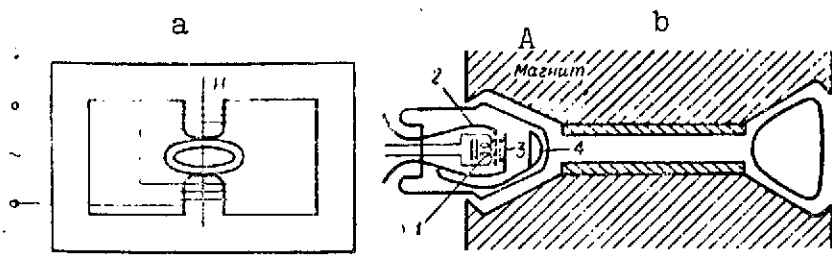


Fig. 17.2. Scheme of betatron (a) and vertical cross section of its inner part (b):

1. Cathode
 2. Grid
 3. Anode
 4. Target
- KEY: A. Magnet

The chamber in which the electrons are accelerated is made of porcelain, plexiglas, or glass. In the course of operation of the betatron, a vacuum up to about 10^{-6} mm Hg must be maintained in its chamber. The electrons arrive in the chamber from an ejector located within the chamber. The electromagnet is powered with alternating current at a frequency in the range 50-800 Hertz.

Using modern betatrons, mean electron currents up to 0.01-0.1 μ A and energies up to 30 Mev can be achieved (some machines can even produce their concurrence with energies to 300 Mev).

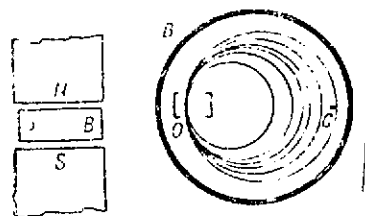


Fig. 17.3. Schematic diagram of microtron (B = vacuum chamber; O = resonator; C = target; and N and S are the electromagnet poles)

L. M. Anan'yev et al. (Tomsk) built portable small betatrons of the PMB type capable of accelerating electrons to 3 Mev with a mean current of 0.06 μ A (PMB-3), 5 Mev with a mean current of 0.012 μ A (PMB-5), and 6 Mev with a mean current of 0.037 μ A (PMB-6). The total weight of these devices is 66, 69, and 128 kg, respectively. The power of the devices from 0.8 to 1.5 kw is provided by line current.

In 1944, V. I. Veksler proposed the microtron, in the USSR. It operates in the region of microwave (centimeter) radio waves, which then was taken as the bases of its name. A schematic diagram of a microtron is shown in Fig. 17.3. In the scheme is depicted three main elements: electromagnet, chamber, and resonator. The electrons are accelerated by means of the resonator in a chamber located between the

poles of a permanent electromagnet. The electrons are fed into the microtron chamber from a special source -- an injector located in the resonator. Electrons injected into the chamber describe a circle in it under the effect of the magnetic field and, on being accelerated, increase their orbital radius with each revolution by means of the high-frequency resonator field. And the acceleration stability is determined by the direct coupling between the frequency of the high-frequency accelerating voltage and the electron revolution frequency.

Electrons in the chamber will travel at speeds close to the speed of light, and with each revolution will usually increase their energy by an amount that is a multiple of their rest energy (0.51 Mev). Thus, the final energy of electrons in a microtron is determined by the number of orbits (m) and is expressed by the formula

$$E_{\text{fin}} = m \Delta E,$$

where ΔE is the increment in the electron energy in one orbit.

Using microtrons, electrons can be accelerated to energies of the order of 50-100 Mev. However, their most rational use is for accelerating electrons to energies of the order of 10 Mev. The mean current in these accelerators can be obtained up to about 50 μA , that is, 50-500 times higher than in a betatron.

At the present time, small-scale devices for geophysical studies are being developed based on the microtron operating principle (Institute of Geology and Geophysics, Siberian Division, USSR Academy of Sciences).

Linear accelerators are also used to produce powerful fluxes of bremsstrahlung x-ray radiation; in these, Van de Graaff and Cockcroft-Walton units, and resonance electron accelerators with wave guides are used as high-voltage generators.

Powerful beams of hard gamma-rays produced in all the devices considered are used in photoneutron analysis of samples based on recording neutrons produced in the reaction (γ, n) , and gamma-activation analysis of samples by the induced activity of isotopes produced in the reactions (γ, γ') , (γ, n) , (γ, p) , and so on.

The content in samples of six elements with sensitivity thresholds from $5 \cdot 10^{-6}$ to 0.01 percent are advantageously determined by photoneutron analysis.

The reaction of nuclear photoexcitation (γ, γ') is used in analyzing elements with atomic numbers $Z > 34$, that is, here the effect of the main rock-forming elements on the results of the analysis can be eliminated. At the present time, this reaction

is used in analyzing elements beginning from selenium and ending with mercury (see Fig. 1.1), with sensitivity thresholds from tenths to hundred-thousandths of a percent, depending on the energy and current of the electron beam, and thus also on the bremsstrahlung gamma-rays.

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The induced radioactivity of isotopes formed in the reactions (γ, n), (γ, p), and others is used in analyzing 26 chemical elements with sensitivity thresholds from hundredths to thousandths of a percent. Here elements with different atomic numbers, that is, light and heavy, can be analyzed. These reactions have different thresholds for the nuclei of atoms of different chemical elements. Therefore, by varying the electron beam energy, it is possible to determine the content of diverse elements in samples.

4. Cyclotron and its Use in Nuclear Analysis

The cyclotron is a cyclic resonance accelerator of nonrelativistic (with velocities below the speed of light) charged particles (ions) with constant magnetic field and alternating electric field (with constant period). This kind of accelerator was proposed in 1929 in the United States by Lawrence and was developed in 1932 jointly with Livingston.

The cyclotron, like the microtron, consists of three main elements: electromagnet, high-frequency resonance generator, and chamber in which ions are accelerated (Fig. 17.4). The ions are introduced into the chamber with an injector. To accelerate the ions, a vacuum of the order of 10^{-6} mm Hg must be continually maintained in the chamber. Using the electromagnet, in the chamber there is produced a magnetic field that is homogeneous and constant with time, with a strength up to $2 \cdot 10^4$ oersteds. Under the effect of this field, particles will travel in the chamber along a circle whose radius is proportional to the particle momentum. Particle acceleration will occur only in the space between the D-electrodes owing to the difference in the potentials, of up to hundreds of thousands of volts produced by the high-frequency electrical field of the resonant generator. After each passage of a particle from one D-electrode to another, the electric field is reversed. Therefore in passing from one D-electrode to the other, each time the particle is accelerated by the value of the voltage applied to the D-electrodes and will travel along a spiral in resonance with the high-frequency field. The acceleration can rise until the ions acquire an energy at which the relativistic effects cannot be neglected.

Overall cyclotron dimensions are determined by the dimensions /131 of the electromagnet, whose diameter can be 1.5-2.25 m. With cyclotrons, protons, deuterons, tritons, helions (helium-3 nuclei), alpha-particles, and heavier ions can be accelerated. Protons and

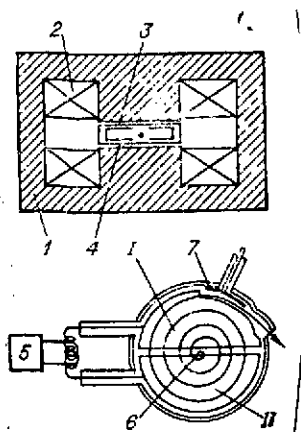


Fig. 17.4 Scheme of cyclotron:

1. Magnet
2. Power winding of magnet
3. Vacuum chamber
4. D-electrodes (I, II)
5. High frequency resonant generator
6. Ion source
7. Deflecting plate

deuterons can be accelerated to a maximum of 25 Mev with beam currents of 1 and 0.3 mA, respectively. Alpha-particles and triply-charged nitrogen atoms can be accelerated to energies of 48 and 160 Mev, respectively, and so on.

Linear accelerators can also be used to produce powerful beams of protons and deuterons, as remarked several times earlier.

The accelerated heavy ions of carbon, nitrogen, oxygen, chlorine, and other elements are used for analysis, based on their scattering from the surface of the irradiated material and studying the induced activity of isotopes produced when the ions react with nuclei of atoms at various chemical elements. From ion scattering one can analyze heavy nuclei of chemical elements differing by unity. This is one of the main advantages of ionic method compared with the others considered above, since here it is possible not only to make an elemental analysis of samples, but also an isotopic analysis. Heavy elements with atomic number of about

200 in a light intervening medium (silica, and so on), when bombarded with carbon ions, can be determined with sensitivity thresholds from 0.001 to 0.1 percent at ion currents of 1 μ A, energy 35 Mev, and measurement time of 5 minutes. Elements in the middle of the periodic system (see Table 1) can be determined beginning at 0.01 percent entire.

Eighty Mev carbon ions are used in lead activation. The induced alpha-activity of the radon-212 produced here ($T = 23$ minutes, $E_{\alpha} = 6.26$ Mev) is measured with a semiconductor alpha-spectrometer. By this technique, it is possible to determine lead beginning at $1 \cdot 10^{-4}$ percent.

Increasingly, when analyzing material in recent years the radiation of accelerated particles such as alpha-particles, helions, tritons, deuterons, and protons, has begun to be used. Thus, deuteron activation analysis is employed in determining in geological samples aluminum, sodium, phosphorus, and boron with sensitivity thresholds from hundredths to ten-thousandths of a percent. Also, the isotopic composition of calcium in minerals is studied by the technique. Proton activation analysis was used by L. P. Starchik and others in analyzing light elements from lithium to sulfur with sensitivity thresholds from hundredths to ten-thousandths of a percent.

CONCLUSIONS

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Dear reader! We are now at the end of our story about nuclear prospectors, which are blazing more and more new trails in the study of the earth's resources and space objects. The time is coming when there will be not a single geological enterprise engaged in searching, prospecting, and exploiting minerals that will not use instruments based on nuclear radiation. As was shown, with their use virtually all chemical elements can be determined in rocks and ores without destruction of the samples, and at times directly in the natural bedding of rocks and ores. All this enables specialists to make prompt necessary decisions in uncovering deposits, exploiting them, and extracting ore, as well as their beneficiation, and so on.

Nuclear prospectors will find growing use also in automatic stations launched by man for the study of space bodies.

It is possible that some readers will be interested in this new field of geophysics and physics and that they wish to select it as their field of future activity. Here some questions are to be expected. Has everything been done in nuclear geophysics? Are there any "blank areas" and "unbeaten paths" in it? It is time to answer these questions.

Nuclear geophysics needs experimenters, theoreticians, and equipment specialists. At the present time, even though a large number of nuclear methods have been developed, many of them are in need of major improvement -- the information content of several techniques must be boosted. This can be achieved, on the one hand, by implementing several new measurement techniques that can lead to increasing the depth at which techniques can operate, and on the other hand, by eliminating background radiation distorting useful signals. Many experimental and theoretical investigations must be conducted in these directions.

Very vital problems also face equipment specialists. First of all, it is necessary to build highly miniaturized devices for geological expeditions, as well as various miniature computers that could quickly process data received and convert it directly for practical use. /133

These miniature devices are needed for cosmonauts on the Moon, Mars, and other planets in building inhabited stations. In the construction of these stations it is necessary to comprehensively study physical and chemical properties of the "building materials." Later the question will arise of processing planetary rocks to obtain oxygen and other vital materials. Nuclear prospectors will be of inestimable service to cosmonauts.

However, nuclear prospectors still face much to do on earth. They must be used in comprehensively studying the earth's depth. Also, the eyes of geologists and geophysicists have already turned to the seas and the oceans -- study of coastal-marine and oceanic deposits has begun, and in several places metallic minerals have begun to be recovered. Petroleum and gas are extracted from beneath the sea bottom. The field of geophysics dealing with these problems is called marine geophysics. However, in contrast to dry-land geophysics, marine geophysics is in its initial stage. This is particularly true of marine nuclear geophysics. A large number of investigations lie ahead both in finding the possibilities of various nuclear methods as well as devising specialized instruments.

And this is only a short list of the nuclear-geophysical tasks (of their full diversity) that is to be solved in the near future.

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